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# Research on ship emission reduction in Guangzhou Port under the policy of Domestic Emission Control Areas (DECAs) in China

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# RESEARCH ON SHIP EMISSION REDUCTION IN GUANGZHOU PORT UNDER THE POLICY OF DOMESTIC EMISSION CONTROL AREAS (DECAs) IN CHINA

By

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**The People's Republic of China**

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## DECLARATION

I certify that all the materials in this research paper that are not my own work have been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this research paper reflect my own personal views, and are not necessarily endorsed by the University.

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**ABSTRACT**

Title of Dissertation: **Research on Ship Emission Reduction in Guangzhou Port under the Policy of Domestic Emission Control Areas (DECAs) in China**

Degree: **MSc**

Ship emission is an important contributor to air pollution, the negative impacts on human health and environment are drawing more and more attention from the world. Recently, China formally issued the policy of establishing Domestic Emission Control Areas (DECAs) in 2015. This paper concentrates on the research of some feasible measures and their effectiveness under DECAs policy in Guangzhou Port.

A brief review of ECAs under MARPOL Annex VI, DECAs in China and the implementation of Guangzhou Port is given, as well as analyzing the features and differences of such policies, to promote a better understanding of emission control areas.

An ship emission inventory of Guangzhou Port in 2016 is built through the AIS assisted activity-based approach to represent the basic ship emission before implementing mandatory measures of DECAs policy. Then the prediction of ship emission inventories of three feasible measures assumed implemented in Guangzhou Port within one year under DECAs policy are produced. By comparing the results and using an AHP tool, the priority of these measures is obtained.

**KEY WORDS:** DECA, Guangzhou Port, activity-based approach, ship emission inventory, AHP

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| | |
|---|---|
| AE | Auxiliary Engine |
| AHP | Analytic Hierarchy Process |
| DECA | Domestic Emission Control Area |
| ECA | Emission Control Area |
| EEA | The European Economic Area |
| EIAPP | Engine International Air Pollution Prevention |
| EMEP | European Monitoring Evaluation Programme |
| GHG | Green House Gas |
| GZMSA | Guangzhou Maritime Safety Administration |
| IMO | International Maritime Organization |
| MARPOL | International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto |
| MD | Maritime Department |
| MDO | Marine Diesel Oil |
| ME | Main Engine |
| MEPC | Marine Environment Protection Committee |
| MGO | Marine Gas Oil |
| MSD | Medium Speed Diesel Engine |
| $NO_x$ | Nitrogen Oxides |
| PM | Particulate Matter |

| | |
|---|---|
| RO | Residual Oil |
| SECA | $SO_x$ Emission Control Area |
| SOLAS | International Convention for the Safety of Life at Sea |
| SOx | Sulfur Oxides |
| SSD | Slow Speed Diesel Engine |
| ST | Steam Turbine |
| USEPA | U.S. Environmental Protection Agency |

# CHAPTER 1
# INTRODUCTION

## 1.1 Background

In recent decades, the air pollution caused by ship emissions is getting more and more serious. According to “Third IMO GHG Study 2014”, emissions of sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$) in 2007-2012 from global shipping accounted for about 15% and 13% of each total amount respectively (IMO, 2015). As ship emissions affects air quality of port areas and threatens ecosystems and human health, Marine Environment Protection Committee (MEPC) of International Maritime Organization (IMO) has set Emission Control Areas (ECAs) through the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL) Annex VI to reduce air pollution from shipping.

In China, the rapid development of economy and the lack of corresponding environmental protection policies have resulted in frequent smog in many areas. Air pollution is becoming more and more serious, and natural environment and public health are under serious threats, arousing the common concern of Chinese society. Relative researches showed that China's annual emissions of $SO_x$ from ships accounted for about 8% of national total $SO_x$ emissions and ship $NO_x$ emissions accounted for about 10% of the national total amount (Peng & Qiao, 2014, pp. 1-5).

The regional distribution of ship emissions mainly concentrated on the Bohai Sea, Yangtze River Delta, Pearl River Delta and other coastal ports. For China's major port cities are densely populated areas, the harmful effects of emissions from ships are much more severe. Communities and experts are looking forward to effective policies dealing with this issue. To improve this situation, the State Council of China has issued “Air Pollution Control Action Plan” in 2013, proposing the idea of setting up ship emission control areas as an option of pollution control. In August 2015, "Ship and Port Pollution Prevention and Special Control Actions Implementation Plan (2015-2020)" was issued by Ministry of Transport of China to promote pollution prevention work of ships and ports. In December of the same year, the formal document of setting Chinese Domestic Emission Control Areas (DECAs), Implementation Plan on Domestic Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and the Bohai Rim (Beijing, Tianjin, Hebei), finally came out and entered into force from 1 January 2016.

Guangzhou is the political, military, economic, cultural and scientific education center of southern China, as well as a huge harbor with over two thousand years' history. As the main port of the Silk Road since the 1930s, Guangzhou became the largest port in China in the Tang and Song dynasties, and the only port for foreign trade in the Ming and Qing dynasties. Nowadays, Guangzhou Port is the 4$^{th}$ largest port in China as well as ranking the 5$^{th}$ in the world by cargo throughput of port, which plays the roles of major material distribution center and the largest international trade hub in Pearl River Delta and South China. Shipping business is highly busy here and population is likewise large, approximately 15,000,000 (Guangzhou Port Authority, 2017). The impacts of air pollution caused by ship emissions are increasingly severe. In the Implementation Plan on Domestic

Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and the Bohai Rim (Beijing, Tianjin, Hebei), Guangzhou Port was defined as a key port in Pearl River Delta DECA, which is a significant part of controlling ship emissions. Guangzhou Port officially began to implement DECA policy on 1 January, 2016 and switched to a stricter standard from 1 January 2017.

### 1.2 Study Purpose

The purpose of this study is to understand the current situation of ship emissions in Guangzhou Port by research and estimate the effectiveness of 3 feasible measures under DECAs policy. Meanwhile, the study will also try to discover the existing problems and give some suggestions to improve the implementation. Distinctions and experience of ECAs under MARPOL Annex VI, other DECAs in China and DECA practice in Guangzhou Port will be elaborated on to understand the issue. To provide data analysis for evaluations and decision making, ship emission inventory of Guangzhou Port in 2016 and prediction of ship emission inventory within one year will be calculated and compared to study the effectiveness of relating measures, and the priority of such measures will be obtained with the assistance of an analytic tool. In accordance with the results of previous steps, problems will be discussed and proposal on improvement will be produced, providing reference for policy makers and implementers to better achieve the designed target.

### 1.3 Methodology and Main Contents

The methodologies used in this study includes theoretical illustration, case analysis, comparative analysis, data collection and the Automatic Identification System (AIS) assisted activity-based approach to produce ship emission inventories, chart analysis and Analytic Hierarchy Process (AHP) by the computer software “Yaahp”.

The main contents consist of the following 5 aspects:

1) Introduction to ECAs under MARPOL Annex VI;

2) Introduction to DECAs policy in China and implementation in Guangzhou Port;

3) Producing ship emission inventory of Guangzhou Port in 2016 and related analysis;

4) Producing prediction of ship emission inventories of three feasible measures under DECAs policy in Guangzhou Port within one year, making comparative analysis with 3) and obtaining the priority by AHP;

5) Drawing conclusions and providing suggestions for better ship emission reduction in Guangzhou Port under DECAs policy according to theory and data analysis above.

# CHAPTER 2

# Introduction to ECAs under MARPOL Annex VI

## 2.1 Historical Progress of ECAs under MARPOL Annex VI

In 1990's, a report submitted by Norway to IMO showed that $SO_x$ emissions from ships had reached 5.5 million tons per year and $NO_x$ emission had reached 5 million tons per year, which accounted 4% and 5% of global total emission of $SO_x$ and $NO_x$ (Zhang, 2014, pp. 17-20). Although these pollutants had been weakened by a wide spread over the sea, they still brought series of environmental problems, such as acid rain, to local areas, posing major threats to human health. The report pinpoints that air pollution caused by ship emissions cannot be ignored anymore.

IMO has been concerned about the impacts of ship emissions on the atmosphere for a long time. MEPC had formally launched the discussion and consideration of preventing air pollution from ships in 1988, the "Prevention of Air Pollution from Ships (Resolution A.719(17))" adopted in IMO Assembly in 1991 instructed MEPC to draft a new Annex to the MARPOL Convention on air pollution from ships. With six years' efforts, the Protocol of 1997 to amend International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto, which added regulations on the prevention of air pollution from ships as the new Annex VI, was finally adopted in the International Conference of Parties to the MARPOL Convention in 1997 (Zhang, 2014, pp. 17-20). In this initial version of MARPOL Annex VI, the Baltic area was designated as a $SO_x$ Emission Control Area (SECA) to implement the limit of sulfur content of fuel used on board not exceeding 1.5% in Regulation 14, while the limit outside SECA was 4.5%.

In 2005, amendments to MARPOL Annex VI (Resolution MEPC.132(53)) was adopted to designate the North Sea as a new SECA.

In 2008, the revised MARPOL VI (Resolution MEPC.176(58)) was adopted, clearly defining that ECA is "*an area where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from $NO_x$ or $SO_x$ and particulate matter or all three types of emissions and their attendant adverse impacts on human health and the environment*", which turned the previous name "SECAs" to "ECAs" and extended the range of air pollutants.

In 2010, the newly adopted amendments to MARPOL Annex VI (Resolution MEPC.190(60)) designated the North American ECA for $SO_x$, $NO_x$ and Particulate Matter (PM), which is the first ECA to deal with 3 types of pollutants.

In 2011, the United States Caribbean Sea ECA was designated as the second ECA for $SO_x$, $NO_x$ and PM with the adoption of amendments to MARPOL Annex VI (Resolution MEPC.202(62)). The historical progress of setting ECAs under MARPOL Annex VI was shown in Figure 1 and the list of these ECAs was shown in Table 1.

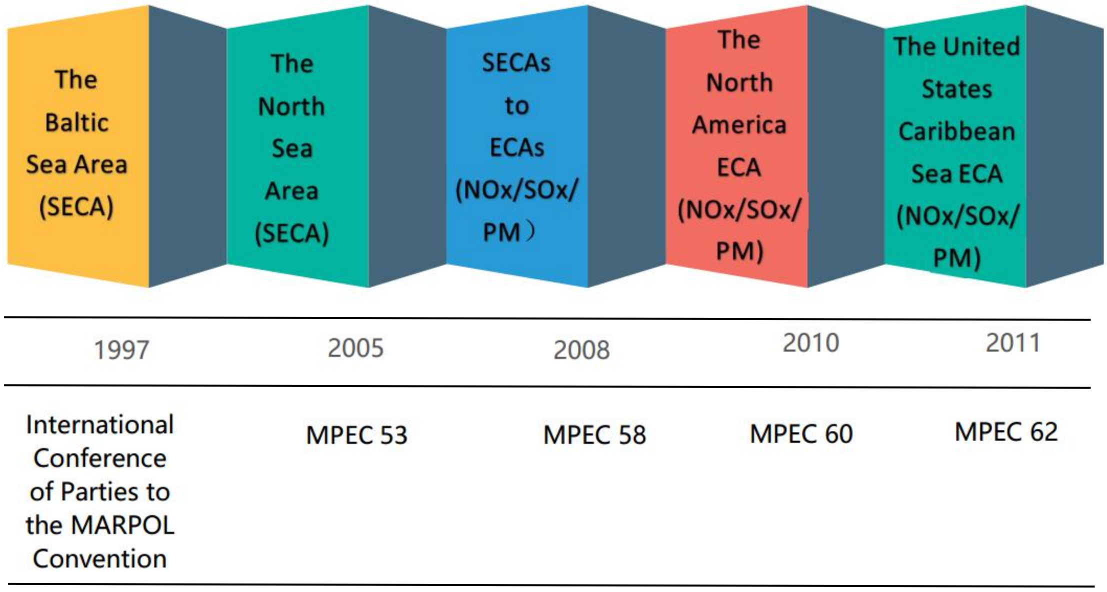


Figure 1- Historical progress of setting ECAs under MARPOL Annex VI

Source: the Author

Table 1- List of existing ECAs under MARPOL Annex VI

| **Special Areas** | **Date of Adoption** | **Date of Entry into Force** | **In Effect from** |
|---|---|---|---|
| Baltic Sea ($SO_x$) | 26 Sept 1997 | 19 May 2005 | 19 May 2006 |
| North Sea ($SO_x$) | 22 Jul 2005 | 22 Nov 2006 | 22 Nov 2007 |
| North American ECA ($SO_x$ and PM) | 26 Mar 2010 | 1 Aug 2011 | 1 Aug 2012 |
| ($NO_x$) | 26 Mar 2010 | 1 Aug 2011 | 1 Aug 2012 |
| United States Caribbean Sea ECA ($SO_x$ and PM) | 26 Jul 2011 | 1 Jan 2013 | 1 Jan 2014 |
| ($NO_x$) | 26 Jul 2011 | 1 Jan 2013 | 1 Jan 2014 |

Source: IMO (web site)

The establishment and improvement of ECAs have not come to a standstill. At MPEC 70 held in 2016, the designation of the North Sea ECA and the Baltic Sea ECA for $NO_x$ was approved for adoption at MEPC 71, and we would see both ECAs to enter into force on 1 January 2021 (IMO, 2016).

**2.2 Category and Distribution of ECAs under MARPOL Annex VI**

ECAs under MARPOL Annex VI can be divided into three types: ECAs for $NO_x$ in accordance with Regulation 13, ECAs for $SO_x$ and PM in accordance with Regulation 14. A sea area can be an ECA for one type of pollutant only or various pollutants. In ECAs, stricter mandatory measures than global requirements on emissions are applied, ships within must meet these requirements or use equivalent methods approved by the Administration according to Regulation 4 of MARPOL Annex VI.


Figure 2- Category and distribution and of existing ECAs under MARPOL Annex VI

Source: Zhang, X. H. (2014). Analysis of international ECAs. *China Ship Survey*, *8*, 17-20.

Currently, there are four ECAs under MARPOL Annex VI, mainly located in Europe and North America. Figure 2 shows the locations and types of these ECAs, they are: the Baltic Sea ECA for $SO_x$, the North Sea ECA for $SO_x$, the North American ECA for $NO_x$, $SO_x$ and PM and the United States Caribbean Sea ECA for $NO_x$, $SO_x$ and PM.

## 2.3 Contents of ECAs under MARPOL Annex VI

### 2.3.1 Requirements on ECAs for $NO_x$

Regulation 13 of MARPOL Annex VI, dealing with emissions of $NO_x$, applies to "*each marine diesel engine with a power output of more than 130kW installed on a ship*". The technical standards for ships are divided into 3 Tiers according to their construction time. As we can see in Table 2 and Figure 3, Tier I is the least stringent emission limit for the operation of marine engines installed on board from 1 January 2000 and prior to 1 January 2011; Tier II is the limit for the operation of marine engines installed on board from 1 January 2011, which requires a 20% reduction of $NO_x$ emission compared with Tier I; Tier III is the most stringent limit for the operation of marine engines installed on board from 1 January 2016 as well as the limit for $NO_x$ ECAs, which requires an 80% reduction of $NO_x$ compared with Tier II; if such engines are only operating outside $NO_x$ ECAs, Tier II limit should be met. Each marine diesel engine regulated by Regulation 13 of MARPOL Annex VI should be surveyed and issued an Engine International Air Pollution Prevention

(EIAPP) Certificate, which is valid for the life time of the engine, and the subsequent demonstration of in-service compliance (Du, 2016).

Table 2- $NO_x$ Emission Standards of Regulation 13 in MARPOL Annex VI

| **Tier** | **Ship construction date (on or after)** | **Total weighted cycle emission limit (g/kWh) n=engine's rated speed (rpm)** | | |
|---|---|---|---|---|
| | | **n<130** | **130≤n<2,000** | **n≥2,000** |
| I | 1 January 2000 | 17 | $45n^{(-0.2)}$ | 9.8 |
| II | 1 January 2011 | 14.4 | $44n^{(-0.23)}$ | 7.7 |
| III | 1 January 2016 | 3.4 | $9n^{(-0.2)}$ | 2 |

Source: International Maritime Organization. (2013). *MARPOL - How to do it*. London: Author.

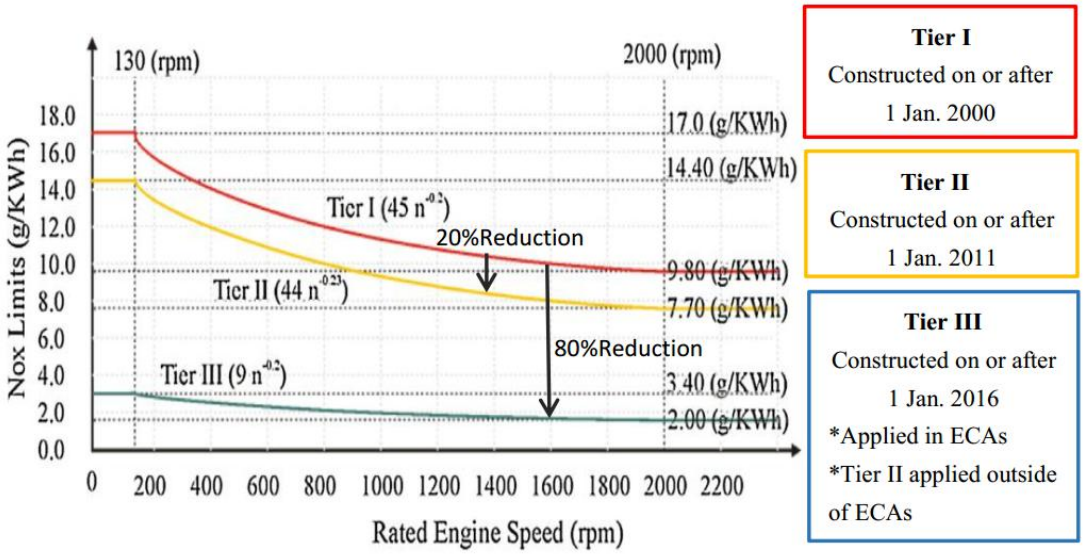


Figure 3- $NO_x$ Emission Control Progress in MARPOL Annex VI

Source: Du, D. CH. (2016). *Marine Environment Protection Standards*. Unpublished lecture handout, Dalian Maritime University, Dalian, China.

### 2.3.2 Requirements on ECAs for $SO_x$ and PM

The requirements on ECAs for $SO_x$ and PM, which are regulated by Regulation 14 of

MARPOL Annex VI, mainly concentrate on the fuel used on board, including distillate fuels and residual fuels used in main engines, auxiliary engines, boilers and inert gas generators. Limiting sulfur content of fuel bunkered and used is the core way of controlling $SO_x$ and PM. Table 3 shows the different limits on sulfur content of fuel used on board inside and outside ECAs.

Table 3- Limits on sulfur content of fuel used on board under MARPOL Annex VI

| **Area** | **Time** | **Sulfur content of fuel (m/m)** |
|---|---|---|
| Global | Before January 1 2012 | 4.50% |
| | After January 1 2012 | 3.50% |
| | After January 1 2020 (Confirmed in MPEC 70) | 0.50% |
| ECAs for $SO_x$ and PM | Before July 1 2010 | 1.50% |
| | After July 1 2010 | 1.00% |
| | After January 1 2015 | 0.10% |

Source: International Maritime Organization. (2013). *MARPOL - How to do it*. London: Author.

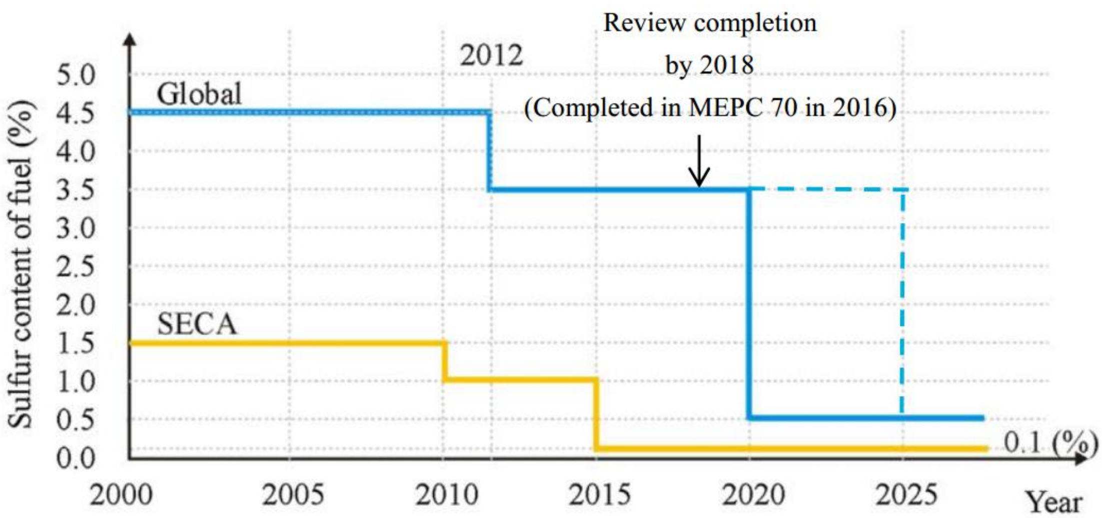

Figure 4- Schedule of implementing limited sulfur content of fuel under MARPOL Annex VI

Source: Du, D. CH. (2016). *Marine Environment Protection Standards*. Unpublished lecture handout, Dalian Maritime University, Dalian, China.

We can learn from Figure 4 that requirements on ECAs are much stricter than global level and the time for implementation is much earlier. Ships operating both inside and outside ECAs are likely to use different fuels to comply with respective limits. An on board written procedure of how to change different fuels are required and the change-over of ECA-compliant fuel must be completed before entering ECAs, as well as that the change-over from ECA-compliant fuel can only begin after exiting ECAs. Each change-over operation should be detailed recorded in the logbook. In addition, the crews should ensure that the ECA-compliant fuel, which the sulfur content has been confirmed by fuel suppliers, are not mixed with non-ECA-compliant fuel during the storage and operations on board, so that the fuel actually used in ECAs will not exceed the limits. Regulation 4 of MARPOL Annex VI also allows equivalent methods to be used in ECAs, as long as approved by the Administrations. For $SO_x$ and PM ECAs, primary methods (such as shore power, clean energy) and secondary methods (such as exhaust gas treatment system) are accepted as alternative measures by a wide range of Administrations.

# CHAPTER 3

# Introduction to DECAs in China and the Implementation in Guangzhou Port

## 3.1 Historical Progress of DECAs in China

As environmental issues being highlighted in recent years in China, remarkable achievements have been made on land-based emissions. By comparison, the harmful impacts of ship emissions were not taken seriously as other emission sources. However, more and more research showed that ship emissions were being a predominant source of air pollution and visible influences on human health and environment were detected in many areas, which attracted more and more attention. To deal with this situation, the Chinese government began to introduce relative policies after years of preparation.

In 2013, “Air Pollution Control Action Plan” was issued by the State Council of China, raising the probability of setting up ship emission control areas;

In August 2015, “Ship and Port Pollution Prevention and Special Control Actions Implementation Plan (2015-2020)” was issued by Ministry of Transport of China, forming the work frame of preventing pollution from of ships and ports;

The revised “Air Pollution Prevention Law of China” adopted in 2015 illustrated that “*Ministry of Transport under the State Council may delineate ship emission control* *areas in coastal waters, ships entering these areas shall meet the relevant emission control requirements*", providing legal basis for the designation of DECAs in China.

In December 2015, the issue of "Implementation Plan on Domestic Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and the Bohai Rim (Beijing, Tianjin, Hebei)" announcing that the DECAs in China were formally established and would entry into force from 1 January 2016.

### 3.2 Distribution of DECAs in China

There are three DECAs along the east coast of China: from south to north lies Pearl River Delta DECA, Yangtze River Delta DECA and Bohai Rim (including Beijing, Tianjin and Hebei) DECAs, as can be seen in Figure 5. Pearl River Delta DECA covers sea zones and inland navigable waters surrounding nine cities such as Guangzhou, Shenzhen and Zhuhai; Yangtze River Delta DECA covers sea zones and inland navigable waters surrounding fifteen cities such as Shanghai, Nanjing and Hangzhou; Bohai Rim (including Beijing, Tianjin and Hebei) DECA covers sea zones and inland navigable waters surrounding thirteen cities such as Dalian, Qinhuangdao and Tianjin. In the meantime, 11 ports such as Guangzhou, Shanghai, Tianjin and Tangshan are determined to be key ports in DECAs (Ministry of Transport of China, 2015). Table 4 lists the detailed geographical ranges of these DECAs.

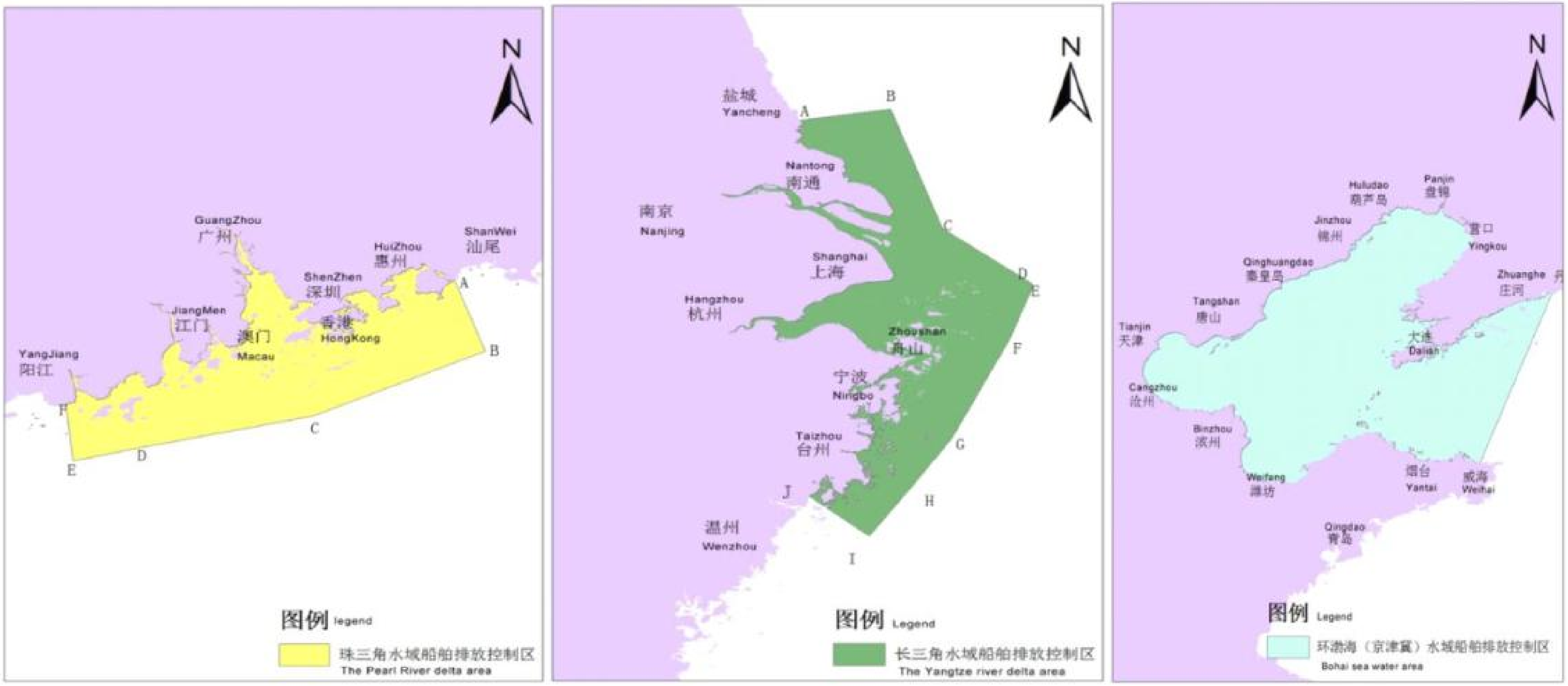


Figure 5- DECAs in China

Source: Ministry of Transport of China, 2015.

Table 4- Detailed geographical ranges of DECAs in China

| DECAs | Sea zones | Inland waters | Key ports |
|---|---|---|---|
| Pearl River Delta | Waters within the lines connecting the points of junction point of shoreline of Huizhou and shoreline of Shanwei, 12 nautical miles (nm) from Zhentouyan, 12 nm from Jia Peng Islands, 12 nm from Wei Jia Island, 12 nm from Da Fan Shi Island,junction point of shoreline of Jiangmen and the shoreline of Yanjiang (excluding the waters of Hong Kong and Macau). | Navigable waters under the administrative jurisdiction of 9 cities, including Guangzhou, Dongguan, Huizhou, Shenzhen, Zhuhai, Zhongshan, Foshan, Jiangmen and Zhaoqing | • Shenzhen<br>• Guangzhou<br>• Zhuhai |
| Yangtze River Delta | Waters within the lines connecting the points of junction point of shoreline of Nantong and shoreline of Yancheng, 12 nm from Wai Ke Jiao Island, 12 nm from Sheshan Island, 12 nm from Hai Jiao, 12 nm from Southeast Reef, 12 nm from Yashan Islands, 12 nm from Taizhou Islands, 12 nm from junction point of theshoreline of Taizhou and shoreline of Wenzhou, junction point of shoreline of Taizhou and shoreline of Wenzhou | Navigable waters under the administrative jurisdiction of 15 cities including Nanjing, Zhenjiang, Yangzhou, Taizhou, Nantong, Changzhou,Wuxi,Suzhou,Shanghai, Jiaxing, Huzhou, Hangzhou, Shaoxing, Ningbo, Zhoushan and Taizhou | • Shanghai<br>• Ningbo-Zhoushan<br>• Suzhou<br>• Nantong |
| Bohai Rim (including Beijing, Tianjin and Hebei) | Waters within the lines connecting the junction point of shorelines of Dandong, Dalian and shorelines of Weihai and Yanta | Navigable waters under the administrative jurisdiction of 13 cities including Dalian, Yingkou, Panjin, Jinzhou, Huludao, Qinghuangdao, Tangshan, Tianjin, Cangzhou, Binzhou, Dongying, Weifang and Yantai | • Tianjin<br>•Qinhuangdao<br>• Tangshan<br>• Huanghua |

Source: Ministry of Transport of China, 2015.

Table 5- Requirements of DECAs policy in China

<table>
<tr><th>Time</th><th>Sulfur content requirement</th><th>Geographical area</th><th>Time period</th><th>Equivalent</th></tr>
<tr><td>From 01/01/2016</td><td>Current standards in international conventions and domestic laws</td><td>All areas</td><td>Period overall</td><td rowspan="5">• Shore power<br>• Clean energy<br>• Exhaust gas treatment system</td></tr>
<tr><td>From 01/01/2016 to 31/12/2016</td><td>Local ports in DECAs can execute higher standards such as requiring ships to use fuel with sulfur content ≤0.5% m/m in accordance with their own conditions.</td><td>Local ports in DECAs with suitable conditions</td><td>Berthing period</td></tr>
<tr><td>From 01/01/2017 to 31/12/2017</td><td>≤0.5% m/m</td><td>Key ports in DECAs</td><td>Berthing period excluding 1 hour after berthing and 1 hour before departure</td></tr>
<tr><td>From 01/01/2018 to 31/12/2018</td><td>≤0.5% m/m</td><td>All ports in DECAs</td><td>Whole berthing period</td></tr>
<tr><td>From 01/01/2019 to 31/12/2019</td><td>≤0.5% m/m</td><td>Whole areas of DECAs</td><td>Whole period when the ship is in DECAs</td></tr>
<tr><td>Before 31/12/2019</td><td colspan="4">An assessment of the effects of the above actions should be produced, to consider if further measures would be taken after 31/12/2019, such as:<br>• use of fuel with 0.1% m/m sulfur content or below<br>• extension of the geographical ranges of DECAs<br>• other further measures</td></tr>
</table>

Source: the Author

### 3.3 Contents of DECAs in China

The policy of DECAs applies to all merchant ships navigating, anchoring and operating in DECAs' scope, except for military ships, sport ships and fishing vessels (Ministry of Transport of China, 2015). Table 5 shows the requirements of DECAs in China.

We can learn from Table 5 that the core of requirements in DECAs policy are limiting the sulfur content of fuel used on board ships, which is the same measure as ECAs for $SO_x$ and PM under MARPOL Annex VI, indicating that current DECAs in China are only controlling emissions of $SO_x$ and PM. The sulfur content limit of fuel used in DECAs is set 0.5% m/m, which is the sole criterion of the policy, but the geographical ranges to implement the policy are extending step by step according to the schedule. Five stages are designed to implement the new requirements: in 2016, requirements can be met voluntarily when ships are berthing in local ports with appropriate conditions; in 2017, requirements should be met when ships are berthing in key ports of DECAs, excluding one hour after berthing and before departure; in 2018, requirements should be met when ships are berthing in all ports within DECAs during the whole period; in 2019, requirements should be met once ships enter DECAs. In addition, shore power, clean energy and exhaust gas treatment system can be accepted as equivalent methods after being approved by the Administration. Before 2020, an effect assessment of DECAs policy will be done and improvements or further measures will be determined, such as executing a more stringent limit of fuel sulfur content, extending the geographical ranges of DECAs, and so on.

### 3.4 Implementation of DECAs Policy in Guangzhou Port

Once the Implementation Plan on Domestic Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and the Bohai Rim (Beijing, Tianjin, Hebei) was issued, Guangzhou's local government, administrations and relevant parties immediately began working for the implementation of the new policy.

Firstly, publishing official notice at the first time. Guangzhou Environmental Protection Bureau, Guangzhou Maritime Safety Administration (GZMSA), Guangzhou Port Authority and Guangzhou Information and Industrialization Committee issued a joint announcement, "Notice on Strengthening Ship Emission Control", to clearly explain the local implementation requirements of the DECAs policy and provide guidance for ships calling at Guangzhou Port (Guangzhou Environmental Pn Bureau et al., 2016). The main points are as following:

- Highlighting the requirements of fuel use in Guangzhou Port under DECAs policy, the detailed implementing schedule and the operational procedures of fuel change-over;
- Organizing and regulating of the fuel suppliers to provide DECA-compliant fuel;
- Encouraging ships to use shore power in wharves with appropriate conditions;
- The use of incinerators on board is forbidden within Guangzhou Port;
- Equivalent methods such as shore power, clean energy and exhaust gas treatment system are accepted in Guangzhou Port under DECAs policy and specific procedures required by the Administration should be undertaken.

Secondly, as the major regulators of DECAs policy, GZMSA has strengthened the supervision of ship emissions. By examining relative documents and undertaking fuel sampling and testing, officers will carry out administrative penalties on ships that violating the regulations in accordance with relative laws. Moreover, a blacklist was made by integrating with the intelligent maritime supervision system, to increase the accuracy and efficiency of supervision.

Last but not least, building regional cooperation with other cities in Pearl River Delta DECA and Macao, as well as Hongkong, which has implemented the local “Air Pollution Control (Ocean Going Vessels) (Fuel at Berth) Regulation” from 1 January 2015. The establishment of coordination mechanisms and information exchange will help constructing a regulatory network, which can greatly enhance the efficiency of regulatory. Simultaneously, the unification of standards and experience sharing will play important roles in effectiveness evaluation and further improve the existing measures.

### 3.5 Comparison of ECAs under MARPOL Annex VI with DECAs in China

Table 6 shows the comparison of ECAs under MARPOL Annex VI with DECAs in China (taking Shanghai Port and Guangzhou Port as examples). The procedures of establishment, pollutant controlling types, main requirements and specific actions will be reviewed and differences will be analyzed.

Table 6- Comparison of ECAs under MARPOL Annex VI with DECAs in China (Shanghai Port and Guangzhou Port)

| **Items** | **ECAs under MARPOL Annex VI** | **DECAs in China (Shanghai port)** | **DECAs in China (Guangzhou Port)** |
|---|---|---|---|
| Procedure of establishment | Proposal of designation of ECAs should be submitted by parties to IMO, after assessment and adoption, IMO would make it into force in accordance with Article 16 of MARPOL Convention. | Established in accordance with domestic laws and brought into force through normative documents by Ministry of Transport of China. | Established in accordance with domestic laws and brought into force through normative documents by Ministry of Transport of China. |
| Type | $NO_x$, $SO_x$, PM | $SO_x$, PM | $SO_x$, PM |
| Measure | **$NO_x$:**<br>• Requirements on engines.<br>**$SO_x$:**<br>• Use fuel with low sulfur content;<br>• Equivalent methods:<br>e.g. shore power, clean energy, Exhaust gas treatment system. | **$SO_x$:**<br>• Use fuel with low sulfur content;<br>• Equivalent methods:<br>e.g. shore power, clean energy, exhaust gas treatment system. | **$SO_x$:**<br>• Use fuel with low sulfur content;<br>• Equivalent methods:<br>e.g. shore power,clean energy, exhaust gas treatment system. |

| | | | |
|---|---|---|---|
| Requirement | **$NO_x$:**<br>• Engine in compliance with Tier III standard.<br>**$SO_x$:**<br>• Mandatory fuel sulfur content limit：<br>Before 01/07/2010:1.5%mm；<br>01/07/2010-31/12/2014: 1.0%mm；<br>After 01/01/2015: 0.1%mm. | **$SO_x$**:<br>• Mandatory fuel sulfur content limit：01/04/2016-31/12/2019: 0.5%mm. | **$SO_x$**:<br>• Voluntary fuel sulfur content limit：01/01/2016-31/12/2016: 0.5%mm.<br>•Mandatory fuel sulfur content limit：01/01/2017-31/12/2019: 0.5%mm. |
| Specific action | • Survey and Certification (e.g. EIAPP Certificate);<br>• Written procedure of fuel change-over operation;<br>• Appropriate records;<br>• Sampling and test;<br>• Keeping fuel receipts;<br>• Ensuring sufficient supply of ECA-compliant fuel;<br>• Accepting equivalent methods. | • Written procedure of fuel change-over operation;<br>• Appropriate records;<br>• Sampling and test;<br>• Keeping fuel receipts;<br>• Ensuring sufficient supply of ECA-compliant fuel;<br>• Accepting equivalent methods;<br>• Regional cooperation. | • Written procedure of fuel change-over operation;<br>• Appropriate records;<br>• Sampling and test;<br>• Keeping fuel receipts;<br>• Ensuring sufficient supply of ECA-compliant fuel;<br>• Accepting equivalent methods;<br>• Regional cooperation. |

Source: the Author

The procedures of establishment are totally different between ECAs under MARPOL Annex VI and DECAs in China, as the former is an international consultation with different countries and the latter one is the internal policy of a single country. To designate an ECA, the related parties should submit a proposal with detailed instructions analysis to IMO, then IMO will evaluate the proposal and set the new ECA in the form of amendment to MARPOL Annex VI, the last step is to consider, adopt the amendment and make it enter into force in accordance with Article 16 of MARPOL Convention. The progress may cost several years or even more because too many factors need to be considered and it is always not easy for member states to reach a common consensus, as well as the procedure being complicated itself. On the other side, the establishment of DECAs in China is more efficient and simple. For DECAs are set within the territory of China, the contents such as geographical scope and emission control requirements are decided by Chinese government, and they are adopted according to domestic laws and brought into force through normative documents, which undergoes a relatively short progress (Peng, 2016, pp. 4-8). The autonomy and efficiency of setting DECAs can reasonably match the current environmental and developmental situations of China, which may bring multiplier effect on ship emission reduction.

Types of pollutants to be controlled are also different between ECAs under MARPOL Annex VI and DECAs in China. ECAs are aiming to control $NO_x$, $SO_x$ and PM when DECAs are only set the requirements to control $SO_x$ and PM but without $NO_x$. The reason may be that the control of $NO_x$ concentrates on the requirements of marine diesel engines, which has depends on sound standards and regulations (Peng, 2016, pp. 4-8). However, the technical standards of marine diesel engine in China are not mature enough and the relative regulations are not in place, so it may not be the appropriate time to set $NO_x$ limits in DEACs policy at the moment.

The measures and specific actions undertaken by ECAs under MARPOL Annex VI and DECAs of China on controlling $SO_x$ are similar, but the requirements of DECAs are far below the requirements of ECAs. The limit of sulfur content of fuel used in ECAs has been 0.1% m/m since 1 January 2015, while the same limit in DECAs will still remain 0.5% in 2019 (though the scope of implementing the limit has been extended step by step). The reasons are various: ECAs have been organized and implemented for many years, the interested parties, such as the ship owners or ship operators, oil suppliers and regulators, had a good run and experience as well as the mature low sulfur fuel supply system. The long and strict procedure of establishing ECAs also considers everything in detail and provides a long time for preparation. On the contrary, DECAs is a new thing in China, and challenges exists from changing the chaotic ship fuel supply situation, to the adaption of interested parties (ship side and cost, regulators and rules, fuel suppliers and production) and the local optimization, all of which need time (Wang, 2016, pp. 18-21). It is unrealistic to get everything done at one step and a gradual transition for preparatory work is necessary. By regulating the market and slowly cultivating awareness, more stringent standards can be implemented to achieve more ambitious goals.

From Table 6 we can also learn that Yangtze River Delta DECA (Shanghai port) had implemented the mandatory fuel sulfur content limit in advance on 1 April 2016, being eight months ahead of the policy schedule which Pearl River Delta DECA (Guangzhou Port) follows. Since Yangtze River Delta DECA was set to be a pilot project, the experience concluded, existing problems and final solutions in Yangtze River Delta DECA will serve the best guide for other DECAs.

# CHAPTER 4

## Building Ship Emission Inventory of Guangzhou Port in 2016

As a key port in the Pearl River Delta DECA, Guangzhou Port started to implement the DECAs policy at the first time. This chapter takes Guangzhou Port as the research object, building the ship emission inventory of 2016, including calculation of the total amount of ship emissions in 2016 through the "AIS assisted activity-based approach" and analysis of the contribution characteristics of various pollutants, in order to provide a basic standard for the next step that predicting and comparing the effects of three feasible measures under DECAs policy.

### 4.1 Geographical Scope

Guangzhou Port is located at 23° 04′ N, 113° 15′ E, extending along the Pearl River coast and water areas in the city of Guangzhou to about 40 nautical miles from the estuary, which consists of Downtown Port Area, HP Port Area, Xinsha Port Area, Nansha Port Area, Pearl River Estuary Anchorage and the Channel. Figute 6 shows the boundary line of the port area. There are 807 berths, 23 buoys and 88 anchorages in Guangzhou Port, the dredging of the port allows one-way navigation of 100,000 tons vessels or two-way navigation of 50,000 tons vessels to enter Nansha terminal in low tide (Guangzhou Port Authority, 2017). The geographical scope of this study covers all berths, buoys, anchorages and major fairway network of Guangzhou Port.


Figure 6- Geographical scope of Guangzhou Port

Source: Guangzhou Port Company Limited (web site)

### 4.2 Methodology and Materials

#### 4.2.1 Fuel-based Approach and Activity-based Approach

The methodologies of building ship emission inventories are usually divided into fuel-based approach and activity-based approach. Fuel-based approach utilizes fuel consumption data of vessels and fuel-based emission factors to calculate emissions (Winther, 2008, pp. 4632-4655), when activity-based approach makes use of fractional load of equipment on board during different vessel activity modes and emission factors to produce emission inventories (Yau, 2012, pp. 299-306). Because of requiring more detailed data such as engine's workload, location, duration, ship speed, routing, and so on, activity-based approach is generally considered to be more accurate than fuel-based approach (Wen, 2015, pp. 96-101). Recently, more and more studies adopted AIS data into activity-based approach to get even more accurate results (Cheng, 2016, pp. 1-10).

AIS is a new type of digital navigational equipment integrating communication technology and electronic information display technology, which can provide four types of information: ship’s dynamic information (location, speed, sailing time, etc), ship’s static information (ship’s name, identification number, size, etc), ship’s navigational information (destination, draft, estimated arrival time, etc) and security information (broadcasting, message notification, etc) (Ye, 2014). Moreover, in accordance with the International Convention for the Safety of Life at Sea, 1974, as amended (SOLAS), merchant ships with gross tonnage of 300 tons and above engaged in international voyages, merchant ships with gross tonnage of 500 tons of above not engaged on international voyages and passenger ships of all size are required to install AIS equipment on board for traffic management and navigation safety, as well as maintaining AIS in operation in all time (IMO, 1999).

The SOLAS Convention's mandatory requirements for AIS provide a comprehensive and stable information source for the activity-based approach on building emission inventory. Static information can help identifying the composition of ships in study areas and accurately grasping proportions and characteristics of various types of ships; dynamic information can be used to estimate the engine load and activity time; using AIS to analyze the flow of ships under specific conditions will help better grasp the characteristics of ship's activities, so as to provide high-precision activity level data and relevant parameters needed for the estimation (Song, 2015).

### 4.2.2 Methodology of Building Ship Emission Inventory

According to "U.S. Environmental Protection Agency Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories Final Report" by ICF International, the activity-based approach was taken to estimate emissions from individual ship call, the equations used are (ICF International, 2009):

To the Main Engine (ME) and Auxiliary Engine (AE) of ships, the equation of estimating emissions is：

$$E_e = P \times LF \times A \times EF \tag{1}$$

where Ee= Emission from engine (g)

P= Engine power (kW)

LF= Engine load factor (percent)

A= Ship activity time (h)

EF= Emission factor (g/kW-h)

Thereinto, for the ME, the Load Factor (LF) is estimated by the Propeller Law based on the equation:

$$LF = (AS / MS)^3 \tag{2}$$

Where LF=Engine load factor (percent)

AS= Actual speed (knots)

MS= Maximum speed (knots)

Ship activity time is obtained by ship traveling distance and actual speed as the equation:

$$A = D / AS \tag{3}$$

Where A= Ship activity time (h)

D= Distance (km)

AS= Actual speed (knots) = Actual speed (km/h)

For boilers of ships, emission is estimated by the equation:

$$E_b = BE \times A \times EF \tag{4}$$

Where Eb= Emission from boiler (g)

BE= Boiler energy (kW)

A= Ship activity time (h)

EF= Engine emission factor (g/tonne of fuel)

### 4.2.3 Research Categorizations

#### *4.2.3.1 Pollutant Type*

According to "USEPA Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories", "EMEP/EEA air pollutant emission inventory guidebook 2016" (European Environment Agency, 2016) and relative studies, $SO_x$, $NO_x$, $PM_{10}$, $PM_{2.5}$, HC and CO are set as target pollutants in building ship emissions inventory of Guangzhou Port in 2016.

#### *4.2.3.2 Ship Type*

According to the actual situation of ship calling at Guangzhou Port in 2016, the types of ships used in the study includes: oil tankers, gas carriers, chemical carriers, bulk carriers, container ships, Ro-Ros, tugs and passenger ships /ferries.

#### *4.2.3.3 Ship Tonnage*

Ships calling at Guangzhou Port are divided into 5 classes by Gross Tonnage (GT) according to the statistical standard of the Maritime Department (MD) of Guangzhou: GT＜1,000; GT 1,000-2,999; GT 3,000-9,999; GT 10,000-49,999; GT≥50,000.

#### *4.2.3.4 Source of Emissions on Board*

Sources of emissions on board include ME, AE and boiler in the study.

#### *4.2.3.5 Ship Activity Mode*

Four ship activity modes are set in the study: fairway cruise, slow cruise, manoeuvring and berthing.

### 4.2.4 Acquisition of Data

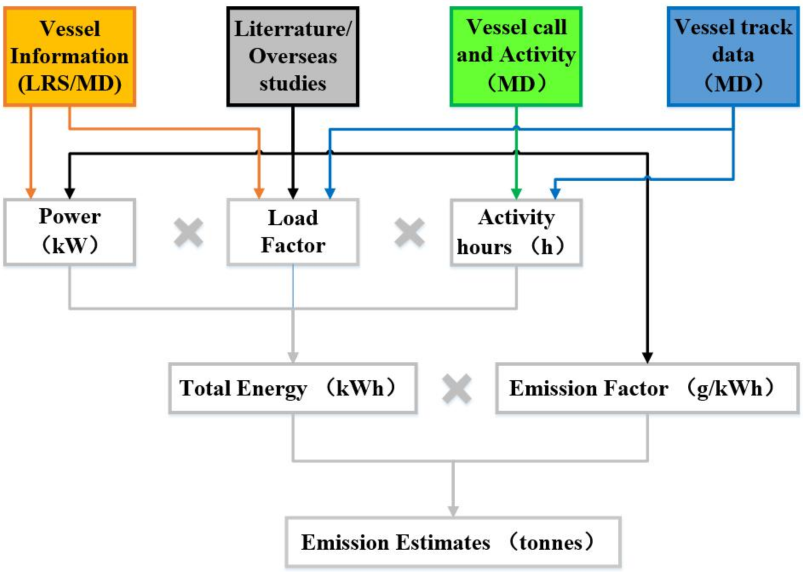

Figure 7- Progress of data acquisition

Source: Ng, S. et al. (2013). Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. *Atmospheric Environment*, *76*, 102-112.

As shown in Figure 7, the data used in building the ship emission inventory was mainly from 4 sources. Ship's basic information including main engine power and maximum speed used to calculate load factor were collected from professional marine database, such as Lloyd's Marine Database, and the MD. The information which were not available by direct and local acquisition, such as AE power, EF, were selected from domestic and overseas literature or relative studies. The actual speed used to calculate LF and ship activity time were from the statistic of the MD, as well as ships' track data by AIS systems.

#### *4.2.4.1 Ship Calling at Guangzhou Port in 2016*

The information of ship calling at Guangzhou Port in 2016 was collected from the MD of Guangzhou, the detailed number and proportion of different ship types and different GT classes are shown in table 7 and figure 8. The total number of ship calling at Guangzhou Port in 2016 was 19,181. Oil tankers, container ships and balk carriers took the largest proportions, accounting for 28.85%, 25.57% and 25.31% respectively; followed by chemical carriers and tugs, which accounted for 5.59% and 5.36%. The rest part including Ro-Ros, gas carriers and passenger ships/ferries only took the proportion of about 9% together.

Table 7- Ship calling at Guangzhou Port in 2016

| Ship type | Number of arrival | Percentage |
|---|---|---|
| **Oil tanker** | **5534** | **28.85%** |

| | | |
|---|---|---|
| GT＜1,000 | 3002 | 15.65% |
| GT 1,000-2,999 | 1606 | 8.37% |
| GT 3,000-9,999 | 578 | 3.01% |
| GT 10,000-49,999 | 300 | 1.56% |
| GT≥50,000 | 48 | 0.25% |
| **Gas carriers** | **550** | **2.87%** |
| GT＜1,000 | 0 | 0.00% |
| GT 1,000-2,999 | 449 | 2.34% |
| GT 3,000-9,999 | 67 | 0.35% |
| GT 10,000-49,999 | 34 | 0.18% |
| GT≥50,000 | 0 | 0.00% |
| **Chemical carriers** | **1073** | **5.59%** |
| GT＜1,000 | 85 | 0.44% |
| GT 1,000-2,999 | 353 | 1.84% |
| GT 3,000-9,999 | 414 | 2.16% |
| GT 10,000-49,999 | 221 | 1.15% |
| GT≥50,000 | 0 | 0.00% |
| **Bulk carriers** | **4855** | **25.31%** |
| GT＜1,000 | 67 | 0.35% |
| GT 1,000-2,999 | 1775 | 9.25% |
| GT 3,000-9,999 | 767 | 4.00% |
| GT 10,000-49,999 | 2174 | 11.33% |
| GT≥50,000 | 72 | 0.38% |
| **Container ships** | **4905** | **25.57%** |
| GT＜1,000 | 168 | 0.88% |
| GT 1,000-2,999 | 1069 | 5.57% |
| GT 3,000-9,999 | 616 | 3.21% |
| GT 10,000-49,999 | 1682 | 8.77% |
| GT≥50,000 | 1370 | 7.14% |
| **Ro-Ros** | **738** | **3.85%** |
| GT＜1,000 | 0 | 0.00% |
| GT 1,000-2,999 | 0 | 0.00% |
| GT 3,000-9,999 | 70 | 0.36% |
| GT 10,000-49,999 | 456 | 2.38% |

| | | |
|---|---|---|
| GT≥50,000 | 212 | 1.11% |
| **Tugs** | **1028** | **5.36%** |
| GT＜1,000 | 919 | 4.79% |
| GT 1,000-2,999 | 97 | 0.51% |
| GT 3,000-9,999 | 12 | 0.06% |
| GT 10,000-49,999 | 0 | 0.00% |
| GT≥50,000 | 0 | 0.00% |
| **Passenger ships /ferries** | **498** | **2.60%** |
| GT＜1,000 | 138 | 0.72% |
| GT 1,000-2,999 | 224 | 1.17% |
| GT 3,000-9,999 | 98 | 0.51% |
| GT 10,000-49,999 | 34 | 0.18% |
| GT≥50,000 | 4 | 0.02% |
| **Total** | **19181** | **100.00%** |

Source: the Author

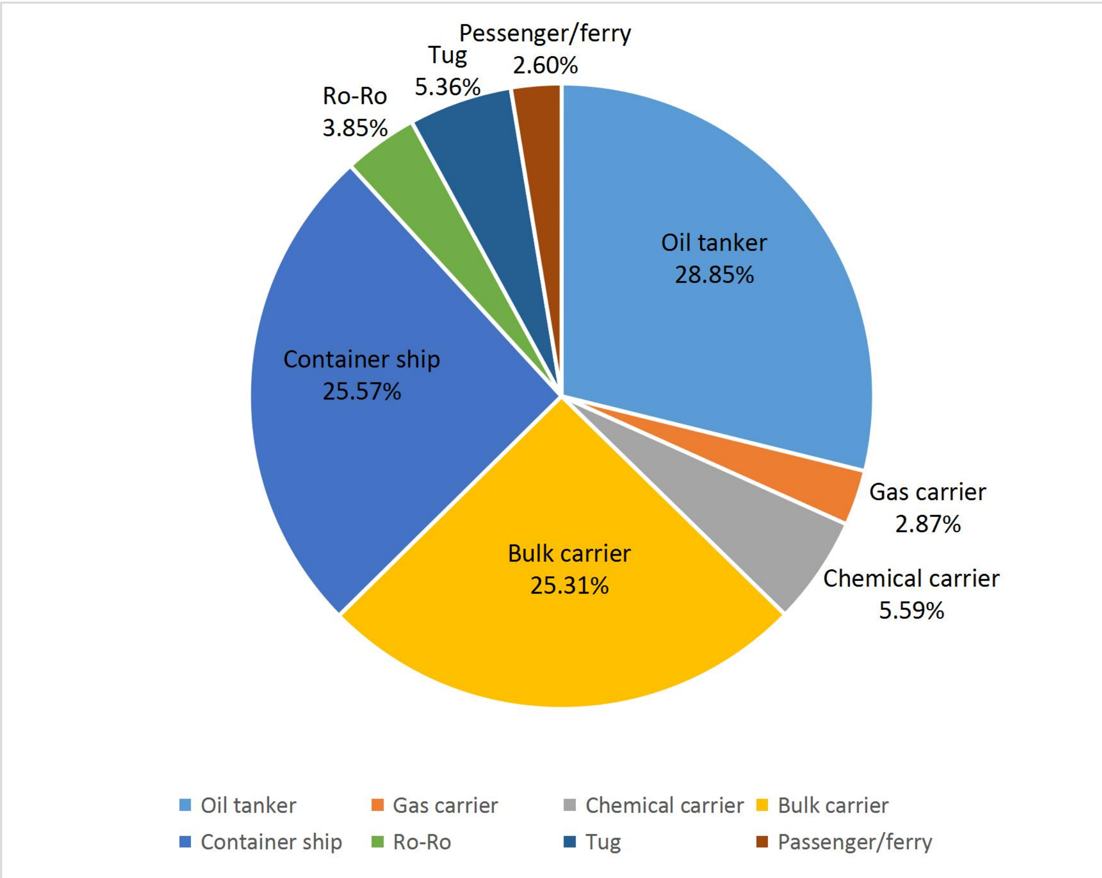

Figure 8- Proportions of different ship types arriving at Guangzhou Port in 2016

Source: the Author

#### *4.2.4.2 Engine Power*

As the ship's basic information, engine power data were collected form ship files of Lloyd's Marine Database and the MD of Guangzhou. 500 sample ship files of various engine power and GT class were collected and the average ME power values were obtained, as shown in Table 8. However, the AE power information was not provided sufficiently by the data sources above as well as other comprehensive sources. So the AE to ME power ratio from the report of ICF International were used as an alternative. The ratios and detailed average AE power values are also shown in Table 8.

Table 8- Average ME power and AE power values used in the study

| Ship type | Average ME power (kW) | AE power to ME power ratio | Average AE power (kW) |
|---|---|---|---|
| **Oil tankers** | | | |
| GT＜1,000 | 596 | 0.211 | 126 |
| GT 1,000-2,999 | 1970 | 0.211 | 416 |
| GT 3,000-9,999 | 3839 | 0.211 | 810 |
| GT 10,000-49,999 | 9960 | 0.211 | 2102 |
| GT≥50,000 | 15820 | 0.211 | 3338 |
| **Gas carriers** | | | |
| GT＜1,000 | 732 | 0.211 | 154 |
| GT 1,000-2,999 | 2405 | 0.211 | 507 |
| GT 3,000-9,999 | 4481 | 0.211 | 945 |
| GT 10,000-49,999 | 11300 | 0.211 | 2384 |
| GT≥50,000 | - | 0.211 | - |
| **Chemical carriers** | | | |

| | | | |
|---|---|---|---|
| GT＜1,000 | 736 | 0.211 | 155 |
| GT 1,000-2,999 | 2574 | 0.211 | 543 |
| GT 3,000-9,999 | 4440 | 0.211 | 937 |
| GT 10,000-49,999 | 13085 | 0.211 | 2761 |
| GT≥50,000 | - | 0.211 | - |
| **Bulk carriers** | | | |
| GT＜1,000 | 745 | 0.222 | 165 |
| GT 1,000-2,999 | 1323 | 0.222 | 294 |
| GT 3,000-9,999 | 2970 | 0.222 | 659 |
| GT 10,000-49,999 | 6032 | 0.222 | 1339 |
| GT≥50,000 | 16858 | 0.222 | 3742 |
| **Container ships** | | | |
| GT＜1,000 | 1020 | 0.220 | 224 |
| GT 1,000-2,999 | 2900 | 0.220 | 638 |
| GT 3,000-9,999 | 7200 | 0.220 | 1584 |
| GT 10,000-49,999 | 31972 | 0.220 | 7034 |
| GT≥50,000 | 56070 | 0.220 | 12335 |
| **Ro-Ros** | | | |
| GT＜1,000 | - | 0.259 | - |
| GT 1,000-2,999 | - | 0.259 | - |
| GT 3,000-9,999 | 8640 | 0.259 | 2238 |
| GT 10,000-49,999 | 17987 | 0.259 | 4659 |
| GT≥50,000 | 22890 | 0.259 | 5929 |
| **Tugs** | | | 0 |
| GT＜1,000 | 2942 | 0.222 | 653 |
| GT 1,000-2,999 | 4323 | 0.222 | 960 |
| GT 3,000-9,999 | 9000 | 0.222 | 1998 |
| GT 10,000-49,999 | - | 0.222 | - |
| GT≥50,000 | - | 0.222 | - |
| **Passenger ships/ferries** | | | |
| GT＜1,000 | 2868 | 0.278 | 797 |
| GT 1,000-2,999 | 4251 | 0.278 | 1182 |
| GT 3,000-9,999 | 6660 | 0.278 | 1851 |
| GT 10,000-49,999 | 19719 | 0.278 | 5482 |

| | | | |
|---|---|---|---|
| GT≥50,000 | 67200 | 0.278 | 18682 |

Source: the Author

#### *4.2.4.3 Ship Maximum Speed*

Ship maximum speed was collected from the ship files of Lloyd's Marine Database and the MD of Guangzhou. The average maximum speed of 500 sample ships of various types and GT classes were obtained.

#### *4.2.4.4 Ship Actual Speed*

The average ship actual speed in different activity modes were collected from the trajectory information of the MD's AIS system.

#### *4.2.4.5 Ship Traveling Distance*

Ship traveling distances is defined as the actual distance of a round trip. The average ship traveling distances in different activity modes in the study was collected from the navigational trajectory information of MD's AIS system.

#### *4.2.4.6 Ship Activity Time*

Duration in different modes were obtained by corresponding ship traveling distance and ships actually speed in accordance with equation (3), as listed in Table 9.

Table 9- Average duration in different activity modes in Guangzhou Port in 2016 by ship type

| Ship type | Duration (hours) | | | |
|---|---|---|---|---|
| | Fairway cruise | Slow cruise | Manoeuvring | Berthing |
| **Oil tankers** | 0.26 | 3.87 | 3.99 | 26.25 |
| **Gas carriers** | 0.31 | 3.21 | 2.89 | 29.27 |
| **Chemical carriers** | 0.22 | 3.56 | 3.48 | 22.48 |
| **Bulk carriers** | 0.58 | 2.25 | 2.33 | 24.72 |
| **Container ships** | 0.91 | 0.85 | 1.76 | 24.86 |
| **Ro-Ros** | 0.88 | 0.82 | 1.81 | 20.38 |
| **Tugs** | 0.07 | 0.64 | 0.74 | 10.85 |
| **Passenger ships /ferries** | 0.94 | 0.4 | 1.55 | 3.23 |

Source: the Author

#### *4.2.4.7 Load Factor*

Load factor is the ratio of an engine's out power at a given speed to the engine's rated power. According to the Propeller Law, LFs of ME in different activity modes can be calculated by equation (2). LFs of AE vary by ship type and activity mode, which were selected form the report of ICF International. Table 10 and Table 11 list the LFs of ME and AE used in the study.

Table 10- LFs of MEs used in the study

| Ship type | Fairway cruise | Slow cruise | Manoeuvring | Berthing |
|---|---|---|---|---|
| **Oil tankers** | 0.5 | 0.446 | 0.023 | 0 |
| **Gas carriers** | 0.5 | 0.375 | 0.024 | 0 |
| **Chemical carriers** | 0.5 | 0.418 | 0.024 | 0 |

| | | | | |
|---|---|---|---|---|
| **Bulk carriers** | 0.5 | 0.289 | 0.025 | 0 |
| **Container ships** | 0.5 | 0.128 | 0.02 | 0 |
| **Ro-Ros** | 0.5 | 0.131 | 0.02 | 0 |
| **Tugs** | 0.5 | 0.569 | 0.02 | 0 |
| **Passenger ships/ferries** | 0.8 | 0.6 | 0.3 | 0 |

Source: the Author

Table 11- LFs of AEs used in the study

| Ship type | Fairway cruise | Slow cruise | Manoeuvring | Berthing |
|---|---|---|---|---|
| **Oil tankers** | 0.24 | 0.28 | 0.33 | 0.26 |
| **Gas carriers** | 0.24 | 0.28 | 0.33 | 0.26 |
| **Chemical carriers** | 0.24 | 0.28 | 0.33 | 0.26 |
| **Bulk carriers** | 0.17 | 0.27 | 0.45 | 0.26 |
| **Container ships** | 0.13 | 0.25 | 0.48 | 0.19 |
| **Ro-Ros** | 0.15 | 0.30 | 0.45 | 0.26 |
| **Tugs** | 0.17 | 0.27 | 0.45 | 0.22 |
| **Passenger ships /ferries** | 0.80 | 0.80 | 0.80 | 0.64 |

Source: ICF International, 2009.

#### *4.2.4.8 Emission Factors and Low Load Multiplicative Adjustment Factors*

For the testing of ocean-going ships emission factor is very expensive and difficult, there are few data in this area, so is the situation in China. Therefore, the building of ship emission inventory of Guangzhou Port adopted the data obtained in the literature by Entec. The EFs vary according to different engine types and the fuel types. Table 12 and Table 13 list the EFs of MEs and AEs used in the study. Given the actual situation of Guangzhou Port according the MD's statistic, the sulfur content of fuel used on board was set to be 2.7% m/m.

Table 12- Emission factors of MEs used in the study

| Engine type | Fuel Type | Sulfur (m/m) | Emission factors (g/kWh) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $SO_x$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | HC | CO |
| **SSD** | **RO** | **2.70%** | 10.29 | 18.10 | 1.42 | 1.31 | 0.60 | 1.40 |
| | **MDO** | **1.00%** | 3.62 | 17.00 | 0.45 | 0.42 | 0.60 | 1.40 |
| | **MGO** | **0.50%** | 1.81 | 17.00 | 0.31 | 0.28 | 0.60 | 1.40 |
| | **MGO** | **0.10%** | 0.36 | 17.00 | 0.19 | 0.17 | 0.60 | 1.40 |
| **MSD** | **RO** | **2.70%** | 11.24 | 14.00 | 1.43 | 1.32 | 0.50 | 1.10 |
| | **MDO** | **1.00%** | 3.97 | 13.20 | 0.47 | 0.43 | 0.50 | 1.10 |
| | **MGO** | **0.50%** | 1.98 | 13.20 | 0.31 | 0.29 | 0.50 | 1.10 |
| | **MGO** | **0.10%** | 0.40 | 13.20 | 0.19 | 0.17 | 0.50 | 1.10 |
| **ST** | **RO** | **2.70%** | 16.10 | 2.10 | 1.47 | 1.35 | 0.10 | 0.20 |
| | **MDO** | **1.00%** | 5.67 | 2.00 | 0.58 | 0.53 | 0.10 | 0.20 |
| | **MGO** | **0.50%** | 2.83 | 2.00 | 0.35 | 0.32 | 0.10 | 0.20 |
| | **MGO** | **0.10%** | 0.57 | 2.00 | 0.17 | 0.15 | 0.10 | 0.20 |

Source: Entec UK Limited, 2002.

Table 13- Emission factors of AEs used in the study

| Fuel Type | Sulfur (m/m) | Emission factors (g/kWh) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $SO_x$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | HC | CO |
| **RO** | **2.70%** | 11.98 | 14.70 | 1.44 | 1.32 | 0.40 | 1.10 |
| **MDO** | **1.00%** | 4.24 | 13.90 | 0.49 | 0.45 | 0.40 | 1.10 |
| **MGO** | **0.50%** | 2.12 | 13.90 | 0.32 | 0.29 | 0.40 | 1.10 |
| **MGO** | **0.10%** | 0.42 | 13.90 | 0.18 | 0.17 | 0.40 | 1.10 |

Source: Entec UK Limited, 2002.

Moreover, the combustion efficiency of the diesel engine will be reduced due to the low load operation (workload＜20%), resulting in the increasing of ship emission factors, so a low load multiplicative adjustment factor is needed to correct the emission factor of MEs. In this study, the low load multiplicative adjustment factors calculated in the report of ICF International were used to modify the MEs' emission factor under low load state as listed in Table 14.

Table 14- Low load multiplicative adjustment factors for MEs

| Load | $SO_x$ | $NO_x$ | PM | HC | CO |
|---|---|---|---|---|---|
| 1% | 5.99 | 11.47 | 19.17 | 59.28 | 19.32 |
| 2% | 3.36 | 4.63 | 7.29 | 21.18 | 9.68 |
| 3% | 2.49 | 2.92 | 4.33 | 11.68 | 6.46 |
| 4% | 2.05 | 2.21 | 3.09 | 7.71 | 4.86 |
| 5% | 1.79 | 1.83 | 2.44 | 5.61 | 3.89 |
| 6% | 1.61 | 1.60 | 2.04 | 4.35 | 3.25 |
| 7% | 1.49 | 1.45 | 1.79 | 3.52 | 2.79 |
| 8% | 1.39 | 1.35 | 1.61 | 2.95 | 2.45 |
| 9% | 1.32 | 1.27 | 1.48 | 2.52 | 2.18 |
| 10% | 1.26 | 1.22 | 1.38 | 2.20 | 1.96 |
| 11% | 1.21 | 1.17 | 1.30 | 1.96 | 1.79 |
| 12% | 1.18 | 1.14 | 1.24 | 1.76 | 1.64 |
| 13% | 1.14 | 1.11 | 1.19 | 1.60 | 1.52 |
| 14% | 1.11 | 1.08 | 1.15 | 1.47 | 1.41 |
| 15% | 1.09 | 1.06 | 1.11 | 1.36 | 1.32 |
| 16% | 1.07 | 1.05 | 1.08 | 1.26 | 1.24 |
| 17% | 1.05 | 1.03 | 1.06 | 1.18 | 1.17 |
| 18% | 1.03 | 1.02 | 1.04 | 1.11 | 1.11 |
| 19% | 1.01 | 1.01 | 1.02 | 1.05 | 1.05 |
| 20% | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Source: ICF International, 2009.

#### *4.2.4.9 Boiler Energy Default*

Boilers on board are usually used to make Residual Oil (RO) fluid enough to use in diesel engines by heating as well as producing hot water (ICF International, 2009). As Table 15 tells us, when a ship is cruising, boiler can be powered by "economizers" such as exhaust heat recovery systems. When a ship is during maneuvering or berthing, the ME exhaust flow or temperature falls below what is needed for economizers to provide adequate heat, so the fuel-fired boiler will be used.

Table 15- State of ship equipment on board in different ship activity modes

| Mode | Main engine | Auxiliary engine | Boiler |
|---|---|---|---|
| Fairway cruise | on | on | on(powered by economizers) |
| Slow cruise | on | on | on(powered by economizers) |
| Manoeuvring | on | on | on(powered by fuel) |
| Berthing | off | on | on(powered by fuel) |

Source: the Author

To estimate boiler's emission, boiler energy default, emission factor of steam engine and time in different activity modes are needed in accordance with equation (4). In this study, the boiler energy default from were obtained in USEPA Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories (ICF International, 2009), as listed in Table 16.

Table 16- Ship boiler energy defaults (kW)

| Ship type | Fairway cruise | Slow cruise | Manoeuvring | Berthing |
|---|---|---|---|---|
| **Oil tankers** | 0 | 0 | 371 | 3000 |
| **Gas carriers** | 0 | 0 | 364 | 364 |
| **Chemical carriers** | 0 | 0 | 371 | 3000 |
| **Bulk carriers** | 0 | 0 | 109 | 109 |

| | | | | |
|---|---|---|---|---|
| **Container ships** | 0 | 0 | 506 | 506 |
| **Ro-Ros** | 0 | 0 | 109 | 109 |
| **Tugs** | 0 | 0 | 0 | 0 |
| **Passenger ships/ferries** | 0 | 0 | 1000 | 1000 |

Source: ICF International, 2009.

## 4.3 Results and Discussion on Ship Emission Inventory of Guangzhou Port in 2016

### 4.3.1 Total emissions

Table 17- Total ship emissions in Guanghzou Port in 2016 (tons)

| $SO_x$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | HC | CO |
|---|---|---|---|---|---|
| 14697.1 | 8106.5 | 1513.8 | 1390.6 | 271.8 | 657.1 |

Source: the Author

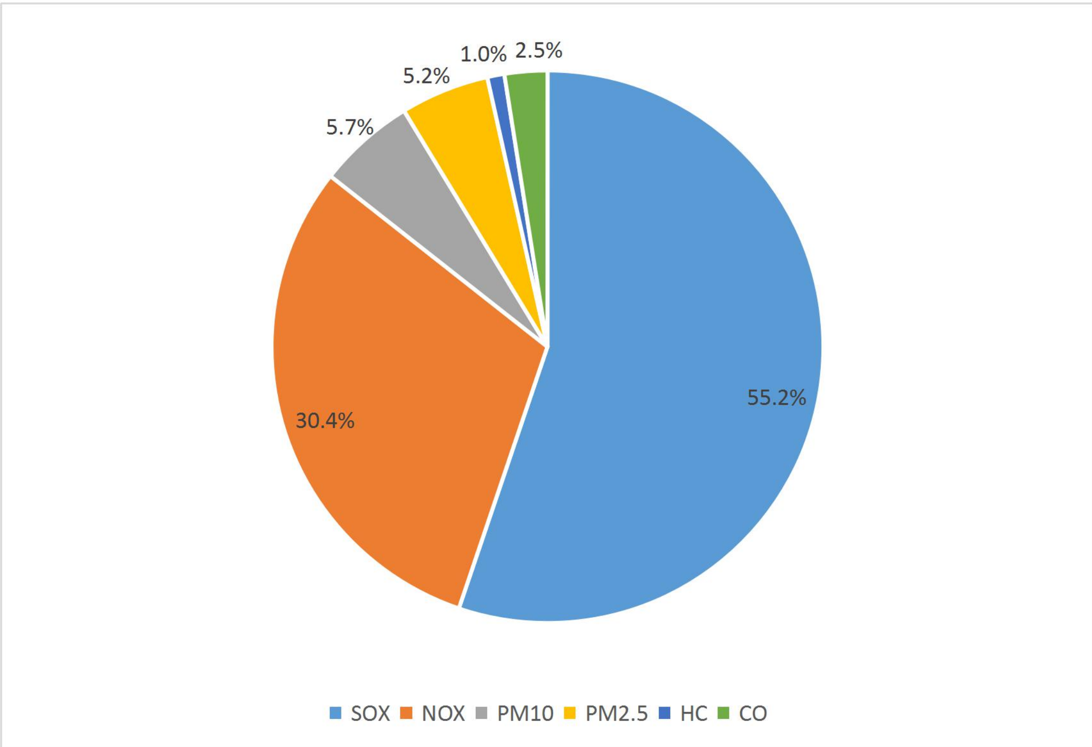

Figure 9- Percentage of each pollutant type in total ship emissions in Guangzhou Port in 2016

Source: the Author

Table 17 and Figure 9 show the total amount and shares of the 6 targeted air pollutants emitted from ships in Guangzhou Port in 2016. Total ship emission of $SO_x$, $NO_x$, $PM_{10}$, $PM_{2.5}$, HC and CO in the whole year were 14697.1 tons, 8106.5 tons, 1513.8 tons, 1390.6 tons, 271.8 tons and 657.1 tons. $SO_x$ was absolutely the most serious pollutant emitted from ships in Guangzhou Port, which accounted for 55.2%. $NO_x$ was another major pollutant following $SO_x$, accounting for 30.4%. $PM_{10}$ and $PM_{2.5}$ had the similar share of ship emissions, approximately 5%-6%. HC and CO emissions from ships in Guangzhou Port were not so obvious compared with other pollutants, together taking the share of 3.5%.

### 4.3.2 Emission Contribution from Different Ship Types

Table 18- Emissions of different ship types in Guangzhou Port in 2016 (tons)

| **Ship type** | **$SO_x$** | **$NO_x$** | **$PM_{10}$** | **$PM_{2.5}$** | **HC** | **CO** |
|---|---|---|---|---|---|---|
| **Oil tankers** | 7632 | 1642.7 | 715.3 | 657 | 67.7 | 146.4 |
| **Gas carriers** | 173.1 | 112.6 | 18.3 | 16.9 | 3.8 | 9.2 |
| **Chemical carriers** | 1405.8 | 475.6 | 136.7 | 125.6 | 17.9 | 40.8 |
| **Bulk carriers** | 846 | 889.8 | 99 | 90.9 | 28.2 | 70.8 |
| **Container ships** | 4084 | 4301.4 | 476.7 | 437.8 | 132.6 | 335.5 |
| **Ro-Ros** | 387.8 | 488.1 | 47.3 | 43.5 | 14.6 | 37.7 |
| **Tugs** | 39.2 | 55.5 | 5 | 4.6 | 1.8 | 4.3 |
| **Passenger ships /ferries** | 129.2 | 140.8 | 15.5 | 14.3 | 5.2 | 12.4 |

Source: the Author

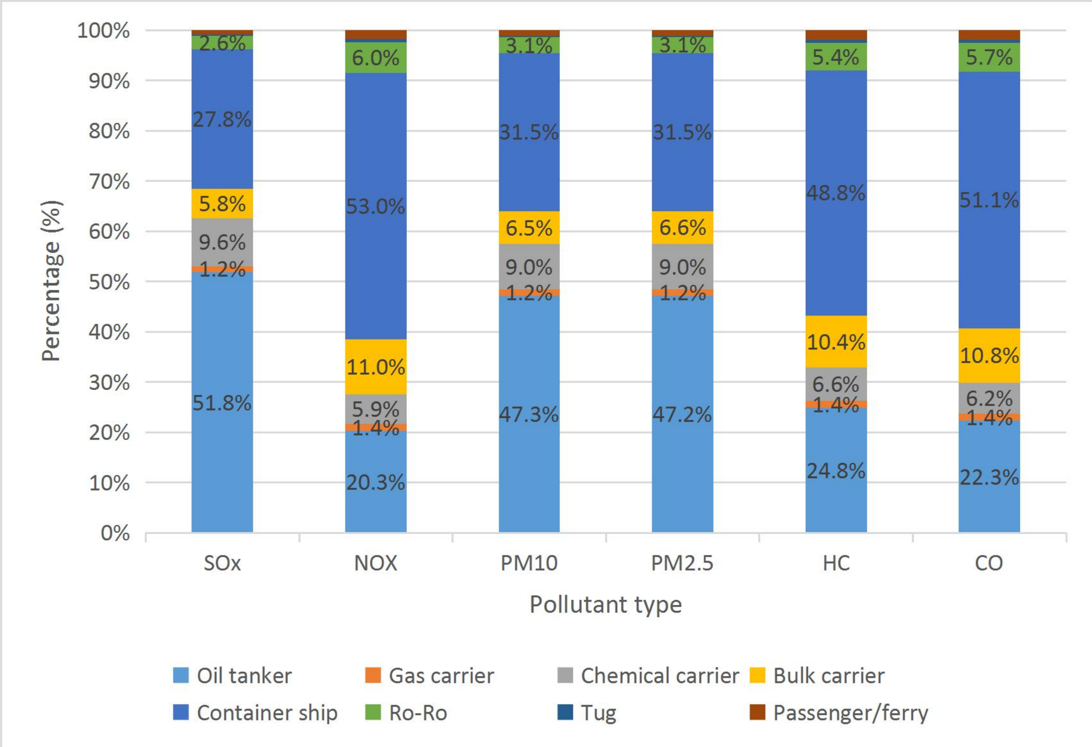


Figure 10- Percentage of different ship types contributing to total ship emissions in Guangzhou Port in 2016

Source: the Author

As can be seen from Table 18 and Figure 10, oil tankers and container ships were the largest sources of emissions in Guangzhou Port, together accounting for more than 70% in each pollutant, for the transportation through ocean-going oil tankers and container ships are very prosperous in Guangzhou Port, which indicates high density and frequency. The contributing proportion of oil tankers and container ships was more than 75% in $SO_x$, $PM_{10}$ and $PM_{2.5}$, because most of them are large ocean-going vessels usually using heavy fuel oil, which contains higher sulfur contents, as fuel, so the combustion will generate more $SO_x$ and PM; meanwhile, the contribution proportions of ships on $SO_x$ and PM were relatively similar, for the fuel with high sulfur contents usually contains more impurities, so they are generated with each other together. Though the ship types contributing to emissions of $NO_x$, HC and CO had similar situations, mainly with container ships and oil tankers taking the largest shares, the amount of $NO_x$ was much larger. The possible reason is that large low speed diesel engines are used as the main driving engine in ocean-going oil tankers and container ships engaged in long-term transport, though the high thermal efficiency makes combustion more completely, the slow speed offers long reaction time for oxygen and nitrogen in the cylinder with appropriate conditions, so that the formation of $NO_x$ is relatively large.

### 4.3.3 Emission Contribution from Different Equipment on Board

Table 19- Emissions of different equipment on board in Guangzhou Port in 2016 (tons)

| Equipment type | $SO_x$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | HC | CO |
|---|---|---|---|---|---|---|
| **Main engines** | 1575 | 2752.6 | 219.8 | 202.8 | 100 | 230.3 |
| **Auxiliary engines** | 3321.5 | 4075.6 | 399.2 | 366 | 110.9 | 305 |
| **Boilers** | 9800.6 | 1278.3 | 894.8 | 821.8 | 60.9 | 121.8 |

Source: the Author

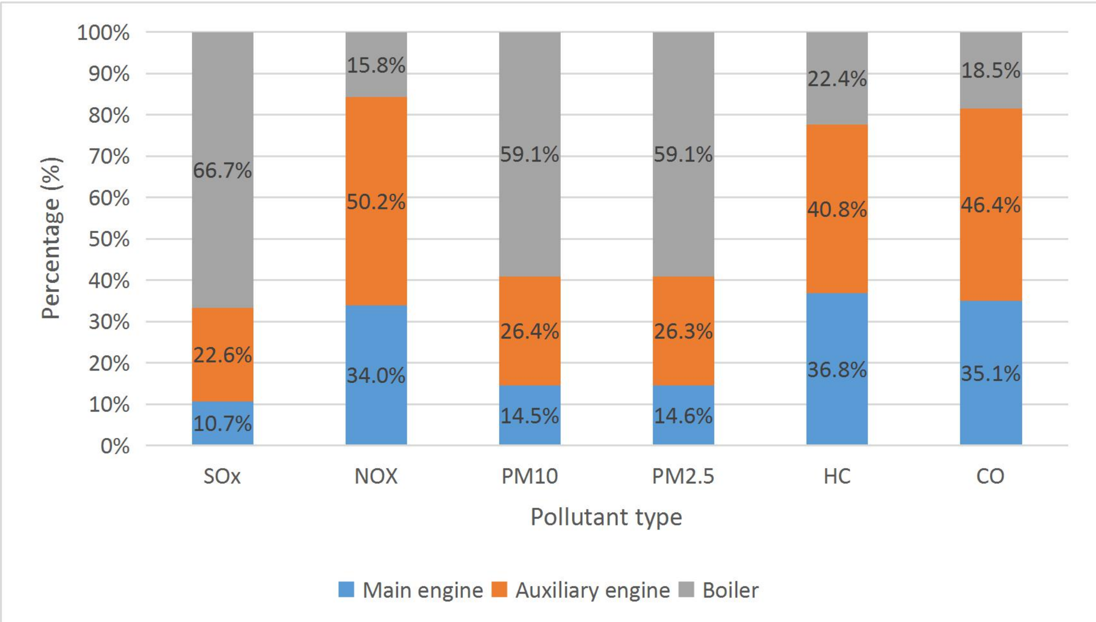

Figure 11- Percentage of different equipment types contributing to total ship emissions in Guangzhou Port in 2016

Source: the Author

It can be seen from Table 19 and Figure 11, emissions of $SO_x$, $PM_{10}$ and $PM_{2.5}$ were mainly from boilers, which accounted for about 60%; followed by AEs, which was between 20%-30%. Emissions of $NO_x$, HC and CO were mainly generated by AEs and MEs, together accounting for more than 80%. ME emissions in all pollutants accounted for relatively low percentage, for when ships are operating in a port, the speed will be reduced, the workload of ME is correspondingly low; when ships are berthing, ME will be closed, only AE and boilers are at work, resulting in lower emissions from ME.

### 4.3.4 Emission Contribution from Different Ship Activity Modes

Table 20- Emissions of different ship activity modes in Guangzhou Port in 2016 (tons)

| **Activity mode** | **$SO_x$** | **$NO_x$** | **$PM_{10}$** | **$PM_{2.5}$** | **HC** | **CO** |
|---|---|---|---|---|---|---|
| **Fairway cruise** | 877.8 | 1510.1 | 120 | 110.7 | 49.6 | 116.6 |
| **Slow cruise** | 809.6 | 1322 | 109.5 | 100.9 | 45.8 | 109.3 |
| **Manoeuvring** | 859.1 | 818.2 | 99.3 | 91.2 | 29.8 | 72.4 |
| **Berthing** | 12150.6 | 4456.2 | 1185 | 1087.8 | 146.6 | 358.8 |

Source: the Author

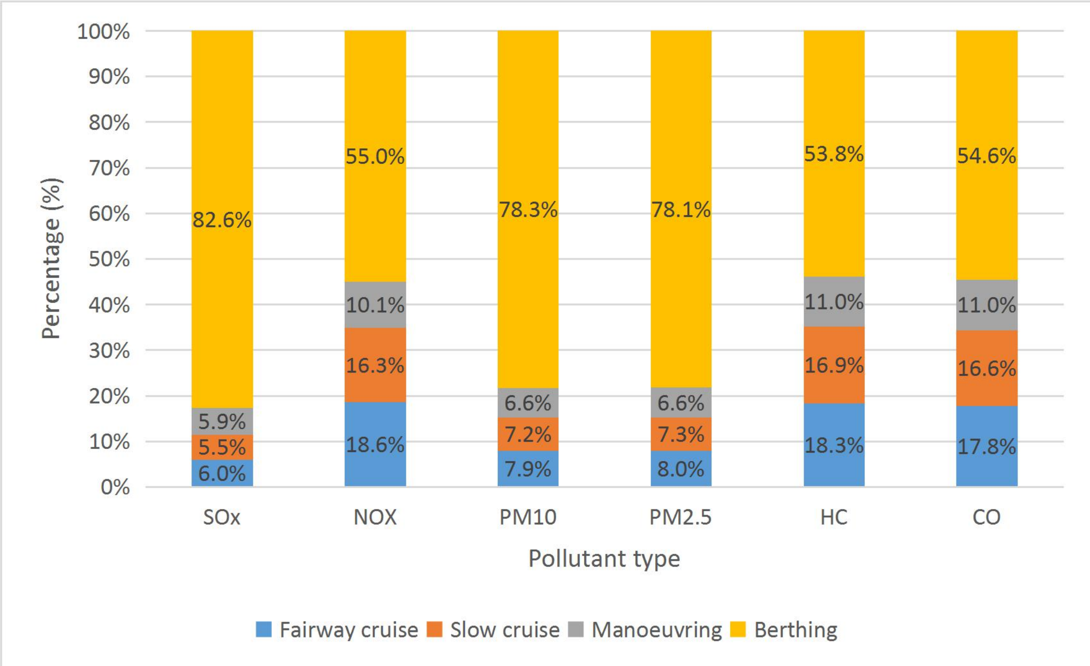


Figure 12- Percentage of different activity modes contributing to total ship emissions in Guangzhou Port in 2016

Source: the Author

It can be seen from Table 20 and Figure 12 that ship's emissions were much larger in berthing mode than the other modes for the time of berthing is significantly longer than any other modes. The berthing modes contributed much more to emissions of $SO_x$, $PM_{10}$ and $PM_{2.5}$, for boilers, a significant source of $SO_x$ and PM, keeps working when ships are at berth, while MEs, the major producer of $NO_x$, HC and CO, are shut down after berthing.

### 4.4 Uncertainty Analysis

Since the calculation of emissions was based on the selections of representative activity level data and emission factors and calculated according to the theoretical equations, as well as that many data was taken with the statistical characteristics of the average, random errors, representativeness or other issues may occur. In addition, uncertainties might also be caused by human errors, data duplication, and lack of key data and sources of inconsistencies in the collection progress of ship activity level data.

Ship's basic information such as the main engine power and speed information were mainly collected from the 500 sample ship files. Seeing that the actual number and types of ships calling at Guangzhou Port might be much more, the limited collection of samples might not fully represent all characteristics of ships arrived, some uncertainties may exist in this part.

Ship's average duration time in different activity modes were mainly collected from the AIS ship trajectory data analysis and estimation. The uneven quality of the collected tracks, which needs artificial adjustment and supplement, might not fully represent all activities of ships arrived, and therefore also leaves some uncertainties.

The information on sulfur content of the fuel used on board was based on the general inspection results provided by the MD and relevant studies. Given different situations of ships and the limited number of inspections, the information was far from being enough, which can only take an average estimate.

Due to the lack of localized data, many parameters of the calculation was based on the results of domestic and overseas studies, such as emission factors, load factors, the main and auxiliary power ratio coefficient and so on. Whether these parameters are suitable to Guangzhou Port is an uncertainty.

## CHAPTER 5

## Effectiveness Evaluation of Three Feasible Measures in Guangzhou Port and Priority obtaining by Analytic Hierarchy Process (AHP)

### 5.1 Description of Measures under DEACs Policy in Guangzhou Port

In Guangzhou Port under DECAs policy, the use of low sulfur content fuel is the most important measure of reducing ship emissions. Although equivalent methods are acceptable (e.g. shore power, clean energy, exhaust gas treatment system, etc.), the pace of which is not as fast as expected. According to the research of Guangzhou Port and the MD of Guangzhou, the use of clean energy and exhaust gas treatment system still has no substantive progress currently, and may not be widely implemented in a short period because these two measures need to make major changes on ships' equipment, which obviously adds extra cost to ship operators, as well as the relative domestic standards and encouraging measures are not sophisticated for the time being, the use of low sulfur content fuel will still be the first choice for the industry.

This chapter will focus on three types of feasible measures that are relatively easy to implement: using low-sulfur content fuel, using shore power and reduction of speed. The prediction of ship emission inventories in Guangzhou Port within one year will be built by assuming that these three measures are implemented respectively. Comparative analysis will be made between the predicted results and the ship emission inventory in Guangzhou Port in 2016 built in Chapter 4 to evaluate the effectiveness of these measures for ship emission reduction. At last, an AHP method will be used to produce a comprehensive priority on these measures and the best option will be obtained.

## 5.2 Feasible Measures Assumed and Calculating Methods

### 5.2.1 Measure 1 (M1): Using Low Sulfur Content Fuel

Assuming that all ships calling at Guangzhou Port use 0.5% m/m sulfur content fuel, corresponding emission factors will be adjusted and ship emissions in Guangzhou Port within one year will be re-estimated.

### 5.2.2 Measure 2 (M2): Using Shore Power

Assuming that all ships berthing at Guangzhou Port are in use of shore power, which means the AEs are shut down during berthing time, the ship emissions in Guangzhou Port within one year will be re-estimated.

### 5.2.3 Measure 3 (M3): Reducing 20% Speed

Assuming that the speed of all ships calling at Guangzhou Port are reduced by 20% from the original, the ship emissions in Guangzhou Port within one year will be re-estimated.

## 5.3 Results and Discussion

Table 21- Prediction of ship emissions in Guangzhou Port within a year after taking 3 assumed measures (tons)

| Emissions | $SO_x$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | HC | CO |
|---|---|---|---|---|---|---|
| **Total emission** | 14697.1 | 8106.5 | 1513.8 | 1390.6 | 271.8 | 657.1 |
| **Emission prediction of using low sulfur content fuel (0.5%) (M1)** | 2587.5 | 7656.6 | 349.8 | 318.5 | 271.9 | 657.1 |
| **Emission prediction of using shore power (M2)** | 12078.7 | 4893.6 | 1199.1 | 1102.1 | 184.4 | 416.7 |
| **Emission prediction of reducing 20% speed (M3)** | 14634.1 | 7996.4 | 1505 | 1382.5 | 267.9 | 647.9 |

Source: the Author

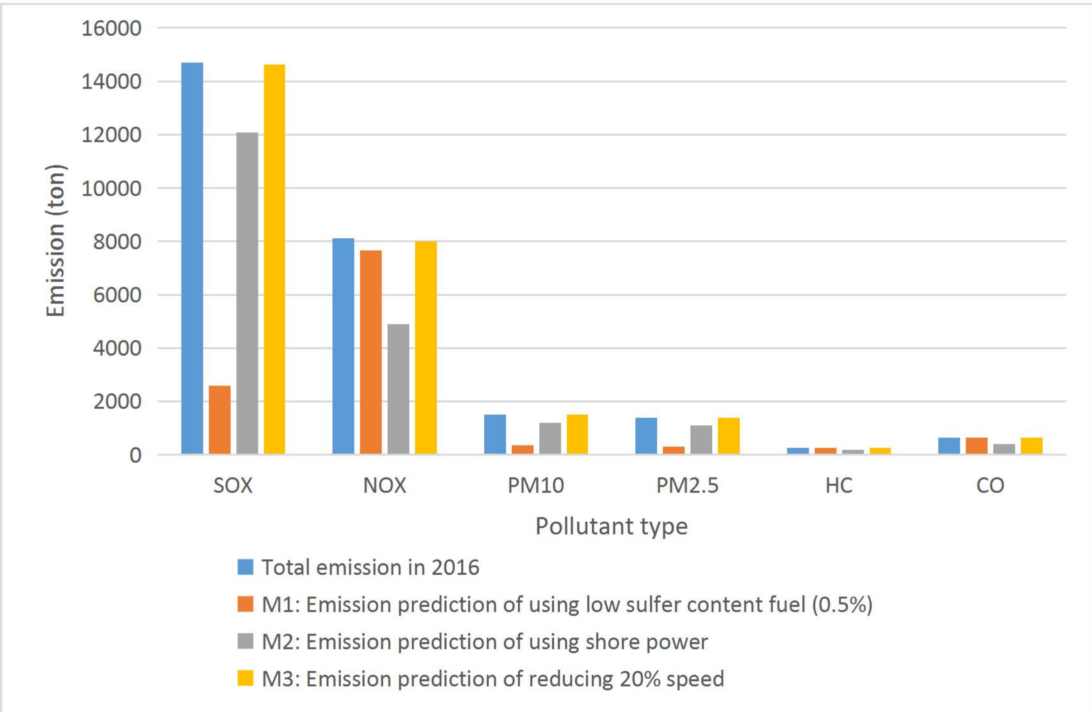

Figure 13- Comparison of ship emission reduction in Guangzhou Port within one year after taking 3 assumed measures

Source: the Author

It can be seen from Table 21 and Figure 13 that the M1 can significantly reduce $SO_x$ emission of ships by 82.4%, $PM_{10}$ by 76.9% and $PM_{2.5}$ by 77.1%; for $NO_x$, HC and CO, the emissions reduction effect is not so obvious as $SO_x$ and PM do. M2 also indicates a certain effect of reducing $SO_x$ emission, $PM_{10}$ and $PM_{2.5}$, which is 17.8%, 20.8%, 20.7%, but not as significant as M1. However, M2 has obvious reducing effects of $NO_x$, HC and CO on the other side, which is 39.6%, 32.2%, 36.6%. M3 approximately does not show any effect on ship emission reduction on all pollutant types, which is commonly less than 2%.

**5.4 Obtaining the Priority of M1, M2 and M3 by AHP**

Analytic Hierarchy Process (AHP) is an effective tool for dealing with complex decision making and assisting decision makers to set priorities of different solutions as well as making the best decision, which was introduced by Thomas Saaty (Guo, 2008, pp. 148-152). By reducing complex decisions to a series of pairwise comparisons and synthesizing the results, AHP helps capturing both subjective and objective aspects of a decision. In addition, a useful technique for checking the consistency of the decision maker's evaluations are incorporated with AHP, thus bias in the decision making process can be reduced effectively. There are 3 steps in AHP, including: defining a problem and modeling it as a hierarchy from goals (top level), criteria (intermediate level) to alternatives (low level); evaluating the hierarchy through a series of pairwise comparisons and consistency checking;

establishing priorities by adding weight values from top to low levels then finally obtaining final priority of the alternatives (Saaty, 2008, pp. 83-98). The AHP application in this study is to obtain the priority and find out the best option for ship emission reduction in Guangzhou Port within one year from M1, M2 and M3. "Yaahp", a well-known domestic AHP software, is used in this chapter.

### 5.4.1 Problem Defining and Hierarchy Modeling

The problem defined is finding the best option from three assumed measures for ship emission reduction in Guangzhou Port within one year. Figure 14 shows the hierarchy modeled from this problem by "Yaahp", and the goal (top level) is to find the best measure to reduce ship emissions in Guangzhou Port within one year, the criteria (intermediate level) to be considered are the reduction effects of 6 pollutants ($SO_x$, $NO_x$, $PM_{10}$, $PM_{2.5}$, HC and CO), the alternatives (low level) are using low sulfur content fuel (M1), using shore power (M2) and reducing 20% speed (M3).

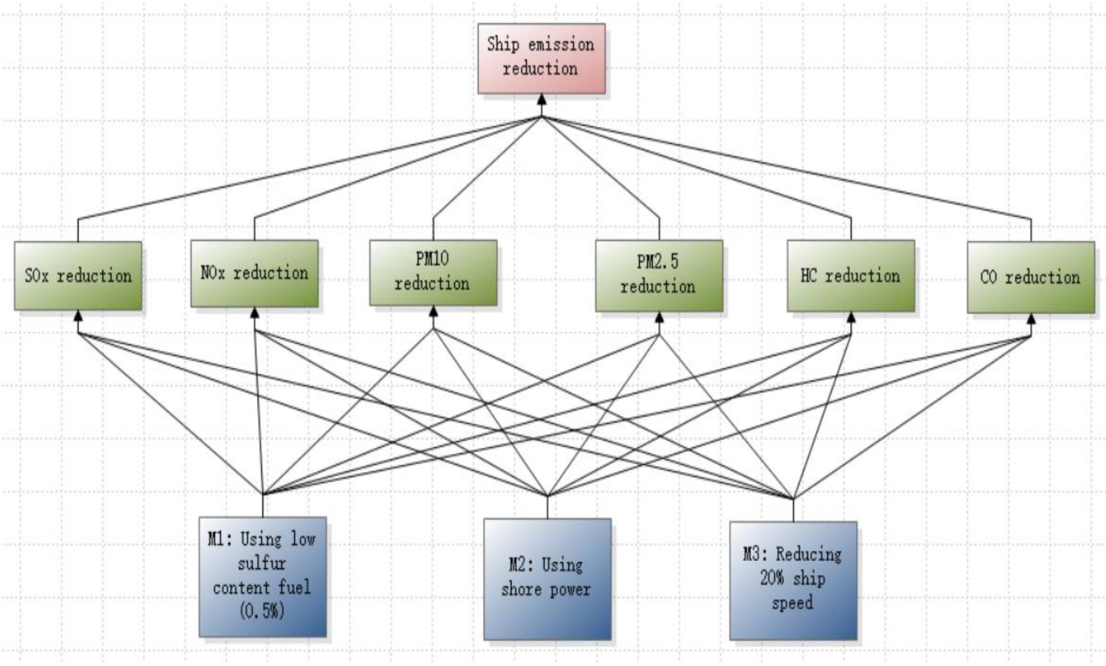


Figure 14- The hierarchy model of ship emission reduction in Guangzhou Port within

one year

Source: the Author

### 5.4.2 Evaluating the Hierarchy through Pairwise Comparisons and Consistency Checking

Table 22- Comparison scale of relative importance

| Scale | Numerical rating | Reciprocal |
|---|---|---|
| Extremely preferred | 9 | 1/9 |
| Very strongly to extremely | 8 | 1/8 |
| Very strongly preferred | 7 | 1/7 |
| Strongly to very strongly | 6 | 1/6 |
| Strongly preferred | 5 | 1/5 |
| Moderately to strongly | 4 | 1/4 |
| Moderately preferred | 3 | 1/3 |
| Equally to moderately | 2 | 1/2 |
| Equally preferred | 1 | 1 |

Source: Saaty, T. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *1*, 83-98.

The comparison scale of relative importance is used to perform pairwise comparisons on elements based on dependency linkages and clusters that influence each other (Saaty, 2008, pp. 83-98). As Table 22 shows, numerical rating from 9 to 2 means the preference form high to low for one element, which means the reciprocal from 1/9 to 1/2 for the other element being compared with. When the numerical rating as well as the reciprocal is equal to 1, these 2 elements are equally preferred.

At this step, weight of each factor are inserted into "Yaahp" to perform pairwise comparisons for evaluation. In the context of the ship emission reduction (the goal), the reductions of 6 pollutant types are made pairwise comparisons with each other. The weight of each pollutant types is set 1, indicating that it is of the equal importance to reduce any of these emissions, as shown in Figure 15. In addition, the calculation of the Consistency Index (CI) of the evaluation is done, which is supposed to be adequate when the value is less than 0.1. The CI of this evaluation is 0 according to Figure 15, which means it has passed the consistency checking.

判断矩阵一致性： 一致 (0.0000)

**Consistency Index**

In the context of

**Ship emission reduction**

Pairwise comparisons

| | SOx reduction | HC reduction | PM10 reduction | CO reduction | NOx reduction | PM2.5 reduction |
|---|---|---|---|---|---|---|
| SOx reduction | | 1 | 1 | 1 | 1 | 1 |
| HC reduction | | | 1 | 1 | 1 | 1 |
| PM10 reduction | | | | 1 | 1 | 1 |
| CO reduction | | | | | 1 | 1 |
| NOx reduction | | | | | | 1 |
| PM2.5 reduction | | | | | | |

Figure 15- Pairwise comparisons in the context of ship emission reduction (the goal)

Source: the Author

The pairwise comparisons in the contexts of $SO_x$, $NO_x$, $PM_{10}$, $PM_{2.5}$, HC and CO reductions (the criteria) are done following the same procedure as shown in Figure 16 to Figure 21, the weights given to each factors are in accordance with the results of Figure 13. In these evaluations, all CIs are in the adequate range.

判断矩阵一致性：　一致 (0.0707)

**Consistency Index**

In the context of

**SOx reduction**

Pairwise comparisons

| | M1: Using low sulfur content fuel (0.5%) | M3: Reducing 20% ship speed | M2: Using shore power |
|---|---|---|---|
| M1: Using low sulfur content fuel (0... | | 8 | 6 |
| M3: Reducing 20% ship speed | | | 1/3 |
| M2: Using shore power | | | |

Figure 16- Pairwise comparisons in the context of $SO_x$ reduction (the criteria)

Source: the Author

判断矩阵一致性：　一致 (0.0279)

**Consistency Index**

In the context of

**NOx reduction**

Pairwise comparisons

| | M1: Using low sulfur content fuel (0.5%) | M3: Reducing 20% ship speed | M2: Using shore power |
|---|---|---|---|
| M1: Using low sulfur content fuel (0... | | 2 | 1/5 |
| M3: Reducing 20% ship speed | | | 1/6 |
| M2: Using shore power | | | |

Figure 17- Pairwise comparisons in the context of $NO_x$ reduction (the criteria)

Source: the Author

判断矩阵一致性：　一致 (0.0624)

**Consistency Index**

In the context of

**PM10 reduction**

Pairwise comparisons

| | M1: Using low sulfur content fuel (0.5%) | M3: Reducing 20% ship speed | M2: Using shore power |
|---|---|---|---|
| M1: Using low sulfur content fuel (0... | | 7 | 5 |
| M3: Reducing 20% ship speed | | | 1/3 |
| M2: Using shore power | | | |

Figure 18- Pairwise comparisons in the context of $PM_{10}$ reduction (the criteria)

Source: the Author

判断矩阵一致性： 一致 (0.0336)

**Consistency Index**

In the context of

**PM2.5 reduction**

Pairwise comparisons

| | M1: Using low sulfur content fuel (0.5%) | M3: Reducing 20% ship speed | M2: Using shore power |
|---|---|---|---|
| M1: Using low sulfur content fuel (0... | | 8 | 7 |
| M3: Reducing 20% ship speed | | | 1/2 |
| M2: Using shore power | | | |

Figure 19- Pairwise comparisons in the context of $PM_{2.5}$ reduction (the criteria)

Source: the Author

判断矩阵一致性： 一致 (0.0279)

**Consistency Index**

In the context of

**HC reduction**

Pairwise comparisons

| | M1: Using low sulfur content fuel (0.5%) | M3: Reducing 20% ship speed | M2: Using shore power |
|---|---|---|---|
| M1: Using low sulfur content fuel (0... | | 1/2 | 1/6 |
| M3: Reducing 20% ship speed | | | 1/5 |
| M2: Using shore power | | | |

Figure 20- Pairwise comparisons in the context of HC reduction (the criteria)

Source: the Author

判断矩阵一致性： 一致 (0.0236)

**Consistency Index**

In the context of

**CO reduction**

Pairwise comparisons

| | M1: Using low sulfur content fuel (0.5%) | M3: Reducing 20% ship speed | M2: Using shore power |
|---|---|---|---|
| M1: Using low sulfur content fuel (0... | | 1/2 | 1/5 |
| M3: Reducing 20% ship speed | | | 1/4 |
| M2: Using shore power | | | |

Figure 21- Pairwise comparisons in the context of CO reduction (the criteria)

Source: the Author

### 5.4.3 Obtaining Final Priority of the Alternatives

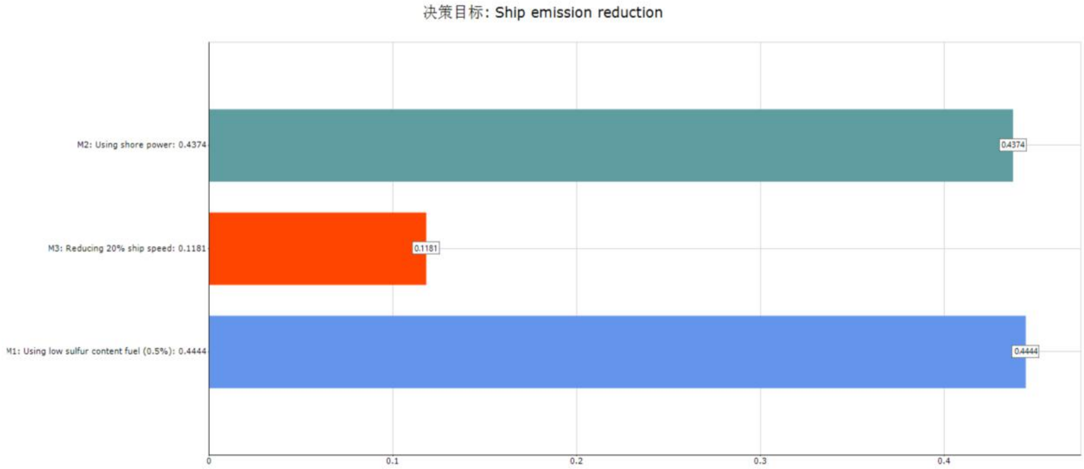


Figure 22- Final weights of M1, M2 and M3

Source: the Author

After previous steps, the final weight of each alternative is produced by the calculation of "Yaahp". It can be seen in Figure 22, the weights of M1, M2 and M3 are 0.4444, 0.4374 and 0.1181, which means the priority of these 3 measures is M1 ＞M2＞M3, indicating that M1 is the best option for the problem defined.

### 5.5 Discussion

According to the results of the predicting inventories and AHP, for Guangzhou Port, using low-sulfur fuel (M1) is the comprehensive best measure for ship emission reduction. The technical threshold of this measure is relative low as well as no necessities to modify the ships and the wharves. The feasibility and simplicity of operation make M1 to be carried out quickly, which leads to significant reductions of $SO_x$ and PM emissions from ships directly. Nevertheless, we can see that the effectiveness of M1 is not so obvious for other pollutant types, for $NO_x$, HC and CO are more with the engine parameters and performance. So the need for more targeted measures (such as engine technologies, modifying existing engines, promoting the advanced engine standards on new ships, the establishment of $NO_x$ emission control areas, etc.) to reduce ship emissions is in demand.

Using shore power (M2) is ranked at the 2nd place, which can reduce a certain amount of various ship emissions. However, due to the high cost of construction and the status of alternative measure in DECAs policy, it is not common in Guangzhou Port. Therefore, it is almost impossible to achieve 100% use of shore power as assumed in the study in a short term, which leads to an actually much less emission reduction. But it can be used as a long-term measure attached to M1, which would undoubtedly promote the effectiveness of ship emission reduction. With the economic and technological development, the distribution of shore power facilities would be more common, and the lower cost, higher efficiency, easy-to-use shore power technologies would probably appear to change this situation. The ship emission reduction from M2 in this study is only a simple estimation and specific effectiveness of this measure needs more in-depth research.

The actual emission reduction effect of reducing 20% speed (M3) is very limited, which can be almost negligible. There may be two reasons: firstly, the reduction of ship speed leads to the increase of duration in each activity mode, it may weaken or even cancel the emission reduction effect caused by the speed reduced according to the definition of equation (1); secondly, when ME is in a low load state, the further reduction of speed may lead to the increase of emission factors by the change of low load multiplicative adjustment factors, which also weaken or offset the emission reduction effect of MEs brought by speed reduction. This study only assumes that the ship speed is reduced by 20% after entering the port to roughly estimate the emission reduction. In practice, due to economic interests, port conditions, weather conditions and other factors, there is a complex calculation method to decide ship speed. Therefore, more in-depth studies with realistic data and professional approaches are needed on this topic.

# CHAPTER 6
## Conclusions and Suggestions

This study comprehensively introduces the ECAs under MARPOL Annex VI, DECAs in China and the implementation of DECAs policy in Guangzhou Port. A comparison of these three is made to study the characteristics of such policies. Then a ship emission inventory of Guangzhou Port in 2016, before the mandatory requirements implemented, is produced through the AIS assisted activity-based approach, followed by the prediction of ship emission inventories in Guangzhou Port within one year after implementing 3 feasible measures under DECAs policy. Comparative studies between these inventories are undertaken and the best measure is obtained through AHP, which is assisted by an AHP computer software “Yaahp”.

Through study, the author draws the following conclusions:

• The establishment of DECAs in China is an important policy to deal with the air pollution from ships as well as a milestone of China's environmental protection actions. On one hand, given the national situations, the DECAs policy is carried out step by step and the emission requirements are gradually upgraded to set appropriate preparation time for shipping industry; on the other hand, the setting of emission requirements has fully considered the global standards of MARPOL Annex VI, which implements a higher fuel sulfur content standard than the current global one (meeting the global standard to be implemented in 2020) to take the responsibility of a contracting state of MARPOL Convention. However, the standards of DECAs in

China are still obviously below the standards of ECAs under MARPOL Annex VI, as well as the coverage of pollutant types, which need to be further optimized and improved.

• Guangzhou Port is the most important port in southern China as well as a key port under DEACs policy. The emissions from ships calling at Guangzhou Port in 2016 were estimated. The results were as follows: $SO_x$ 14697.1 tons, $NO_x$ 8106.5 tons, $PM_{10}$ 1513.8 tons, $PM_{2.5}$ 1390.6 tons, HC 271.8 tons and CO 657.1 tons. $SO_x$ and $NO_x$ are the major pollutants from ships in Guangzhou Port, oil tankers and container ships are the largest sources of ship emissions, boilers and AEs generates the largest part of pollutants and berthing time is the most serious period of emission.

• Within the three feasible measures proposed in the study: using low sulfur content fuel (M1), using shore power (M2) and reducing 20% speed (M3), M1 is the comprehensively best measure for Guangzhou Port to control ship emissions under DECAs policy. However, these measures all need to be further studied.

• According to the prediction of ship emission inventories of Guangzhou Port within a year, the major feasible measures in DECAs have significant effects on reduction of $SO_x$ and PM emissions, but relatively poor effects on $NO_x$, CO and HC reductions, and currently there are not many corresponding targeted measures.

In view of the problems identified in this study, the author puts forward the following suggestions:

Firstly, requirements and targeted measures of controlling $NO_x$ emission should be considered and added to the DECAs policy. Meanwhile, domestic engine technical standards, laws and regulating mechanisms should be established as quickly as possible and continuously improved, to promote effective ship emission reduction for $NO_x$ .

Secondly, the municipal government and related administrations of Guangzhou should introduce more flexible and diversified measures to improve the implementation of DECAs policy. On the one hand, the strict implementation of the policy should be ensured by optimizing the regulatory process and equipping with updated monitoring technologies, which would directly improve regulatory efficiency. On the other hand, the incentive policies to low sulfur content fuel, shore power construction as well clean energy can be used to lead relevant stakeholders to better play their own roles in the policy. At the same time, the raising of the awareness of environmental protection and making an effective publicity also contribute to smoothly implementation of DECAs policy.

Thirdly, a ship emission reduction statistical monitoring system should be established in Guangzhou. The development of accurate emission inventories is the basis for evaluating emission reduction effectiveness, so a sound data maintenance system is needed. The participation of relevant port enterprises, shipping companies and environmental protection department can provide accurate and long-term data continuously. In addition, with the help of technical strength from universities, scientific research institutions and shipping associations as well as the Internet plus platform, the ship emission reduction monitoring, testing and statistical analysis network will finally be built.

Last but not least, new technologies concerning ship emission monitoring should be introduced and applied. Emission monitoring is difficult because of the mobility and proliferation of ships, the inspections only by fuel sampling cannot completely meet the regulatory requirements. Currently, remote control tracking technologies, such as airborne sniffer measurement and fixed ship emission measurement, are very popular in this field in Europe and the United States (Peng, 2014, pp. 1-5). Guangzhou should closely follow the development of such technologies and consider timely introduction of them with prescribed procedures as well as designing the local application, to help the regulators improve their effectiveness and efficiency during supervision.

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